



# PHILIPPINES

## FINANCIAL SECTOR ASSESSMENT PROGRAM

June 2022

### TECHNICAL NOTE ON BANK STRESS TEST FOR CLIMATE CHANGE RISKS

This technical note on Bank Stress Test for Climate Change Risks was prepared by a staff team of the International Monetary Fund and World Bank in the context of a joint IMF-World Bank Financial Sector Assessment Program (FSAP). It is based on the information available at the time it was completed on February 2021.

Copies of this report are available to the public from

International Monetary Fund • Publication Services  
PO Box 92780 • Washington, D.C. 20090  
Telephone: (202) 623-7430 • Fax: (202) 623-7201  
E-mail: [publications@imf.org](mailto:publications@imf.org) Web: <http://www.imf.org>  
Price: \$18.00 per printed copy

**International Monetary Fund**  
**Washington, D.C.**

# PHILIPPINES

## FINANCIAL SECTOR ASSESSMENT PROGRAM

Mav 2022

# TECHNICAL NOTE

## BANK STRESS TEST FOR CLIMATE CHANGE RISKS

Prepared By  
Monetary and Capital Markets  
Department, International  
Monetary Fund and Finance and  
Global Markets Global Practice,  
World Bank

This Technical Note was prepared by IMF and WB staff in the context of the Financial Sector Assessment Program in the Philippines, and overseen by the Monetary and Capital Markets Department, International Monetary Fund, and the Finance, Competitiveness and Innovation Global Practice, World Bank. It contains technical analysis and detailed information underpinning the FSAP's findings and recommendations. Further information on the FSAP program can be found at <http://www.imf.org/external/np/fsap/fssa.aspx>, and [www.worldbank.org/fsap](http://www.worldbank.org/fsap).



INTERNATIONAL MONETARY FUND



THE WORLD BANK

# CONTENTS

Glossary	3
<b>EXECUTIVE SUMMARY</b>	<b>4</b>
<b>INTRODUCTION</b>	<b>7</b>
<b>CLIMATE CHANGE STRESS TEST</b>	<b>13</b>
A. Overview	13
B. Climate Scenario	16
C. Disaster Scenarios	20
D. Macrofinancial Scenario	22
E. Bank Solvency Stress Test	26
<b>POLICY DISCUSSION</b>	<b>29</b>
A. Policy Decision Making Under “Deep” Uncertainty	29
B. Recommendation	30
<b>REFERENCES</b>	<b>44</b>
<b>FIGURES</b>	
1. Power Generation by Source	9
2. FSAP Stress Test for Physical Risks: Key Steps	14
3. Uncertainty in Global Climate Projections	17
4. Uncertainty in Climate Change’s Impact on Typhoon Characteristics in the Philippines	18
5. Anatomy of CAT Models and the Application to FSAP Exercise	20
6. Estimated Physical Capital Losses	22
7. GDP Assumptions for Climate Change Stress Test	26
8. Macroprudential Solvency Stress Tests: A Block Diagram	27
9. Climate Change Stress Test—Impact on Total Bank Capital Ratio	28
<b>TABLES</b>	
1. Recommendations	6
2. Countries with High Natural Hazard and Climate Risk	8
3. Disasters’ Impact on Capital and GDP	25
<b>APPENDICES</b>	
I. Stress Test Matrix	32
II. Macrofinancial Model	37

## Glossary

AE	Advanced economy
AFC	Asian Financial Crisis
AfS	Available for Sale
AR5	The Fifth Assessment Report (by the IPCC)
BoE	Bank of England
BSP	Bangko Sentral ng Pilipinas
CAR	Capital Adequacy Ratio
CAT	Catastrophe (risk model)
DA	Department of Agriculture
DNB	De Nederlandsche Bank
DOE	Department of Energy
DOST	Department of Science and Technology
DRFI	Disaster Risk Financing and Insurance (program of the World Bank)
DSGE	Dynamic Stochastic General Equilibrium (model)
EM	Emerging Markets
EMDE	Emerging Market and Developing Economy
ESG	Environmental, Social, and Governance
FSAP	Financial Sector Assessment Program
FSB	Financial Stability Board
GCM	General Circulation Model
GDP	Gross Domestic Product
GFSR	Global Financial Stability Report
GHG	Greenhouse gas
HtM	Held to Maturity
IC	Insurance Commission
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
LGD	Loss given default
LTV	Loan-to-value
NGFS	Network for Greening the Financial System
NPL	Non-performing Loan
PAGASA	Philippine Atmospheric, Geophysical, and Astronomical Services Administration
PD	Probability of Default
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
SEC	Securities Exchange Commission
STeM	Stress Test Matrix
TFP	Total Factor Productivity
TN	Technical Note
UKB	Universal and Commercial Bank
USD	United States Dollar
WB	World Bank
WEO	World Economic Outlook

## EXECUTIVE SUMMARY<sup>1</sup>

**The Philippines is highly vulnerable to risks from climate change.** The Philippines is categorized as one of the world's most vulnerable countries to climate change and natural disasters, especially typhoons. Depending on where a severe typhoon hits the Philippines, it could potentially cause a systemic impact. All major cities and most of the population reside on the coastline, including the metropolitan Manila area where about 60 percent of economic activities take place. On the other hand, exposures to transition risk are concentrated in the coal-based power generation sector and the government's licensing policy to build new power plants.

**While transition risks are also important, this FSAP focused on the risk assessment of banks to physical risks from climate change.** The Philippines' current policies are still short of achieving the goal set by the Paris Agreement. However, they appear to put the country closer to achieving the goal than advanced economies and several large emerging market economies. The cost of transition may be relatively small compared to other economies that are well behind the goal. Moreover, given the frequent typhoons, there exist substantial research on the implication of global warming to typhoons in the Philippines and their expected damages to infrastructures. These studies allow to construct tailored physical risk scenarios based on solid science. The exercise focuses on the banking sector as it dominates the financial system.

**The FSAP developed a new macro-scenario stress testing method for banks to assess physical risks from climate change.** The main innovation of this exercise is the approach we used to construct scenarios. Scenarios consist of three sub-components: climate, disaster, and macrofinancial scenarios. The climate scenario is based on an existing study about the changes in typhoon intensity and frequency in the future. The disaster scenario is based on the World Bank's catastrophe (CAT) risk model for the Philippines and translates the impact of typhoons on the loss of physical capital. The macrofinancial scenario uses a Dynamic Stochastic General Equilibrium (DSGE) model calibrated for the Philippines. The model calculates the impact of lost physical capital on the economy, reducing production capacity by damaging capital stock and productivity. Then, we estimate the impact on bank solvency using the same approach for macro scenario stress tests for banks.

**Our work uniquely contributes to the literature on climate change stress testing.** To our knowledge, we are the first to link typhoon CAT models to macro scenario stress tests of banks. CAT models consider extreme tail events using simulation, not just historical observations, since most historical data are too short to observe rare events that occur every once in hundreds of years. Furthermore, we explicitly account for climate change effects by considering both current disaster risks and the potential future development of this risk under a chosen climate scenario.

---

<sup>1</sup> This Technical Note has been prepared by Fabian Lipinsky, Paola Morales, and Hiroko Oura (all IMF) and Nicola Ranger, Stephane Hallegatte, Martijn Gert Jan Regelink, and Henk Jan Reinders (all World Bank).

**The simulated scenarios show that extreme typhoons' impact on GDP growth could be systemic in the Philippines.** The paths for GDP show that for both current and future scenarios, typhoons with 10- and 25-year return period give less than one standard deviation shock to GDP, which is also smaller than the shock to the Philippines during the Global Financial Crisis or Asian Financial Crisis episodes. The difference between current and future scenarios is also small. The severity of the GDP impact and the difference between current and future scenarios becomes starker for tail events. In particular, the impact of a 500-year return period typhoon on real GDP is comparable to that of COVID-19. On the other hand, the incremental impact of climate change, measured by the reduction of annual average GDP growth rate in a steady state (-0.12 percentage points per year), appears small, especially given the strong potential growth rate.

**The bank solvency tests examined the effects of tail weather events for three years upon disasters that would occur in 2020 and sometime in the mid-21<sup>st</sup> century.** Since the country already faces disaster risks under current climate conditions, the effects of climate change should be measured as the difference between the impact implied by the current and future likelihood of typhoons. For this purpose, we considered "current scenarios" that start in late 2020 and "future scenarios" that take place at some point in the mid-21<sup>st</sup> century. The bank balance sheet and baseline economic projections in the future scenarios are assumed to be the same as in 2020. For each disaster scenario, we examined three sub-scenarios—baseline without disaster and with once in 25- and 500-years disasters—in order to highlight the range of possibilities rather than point estimates. Moreover, we considered two baselines, one with pandemic (October 2020 World Economic Outlook, WEO, forecast) and the other without (January 2020 WEO forecast). The scenarios with pandemic test the impact of "compound risk"—the risk where multiple tail risks materialize jointly.

**The results show that climate change could cause significant risks to financial stability in a compound shock scenario.** Without other extreme tail events, such as a pandemic, climate change in the future would reduce bank capital ratio visibly only in the tail events once in 500 years. Still, the decline is small at one percentage point. Also, the difference of capital ratios between baseline and a 500-year return period typhoon remains very small—maximum 0.2 percentage points in the current scenario and 0.9 percentage points in the future scenario. However, the possibility of compound risks drastically increases the marginal effects of a typhoon on top of a pandemic even without climate change. With climate change, a joint shock strengthens the additional impact of typhoons by 2.2 and nearly 8 $\frac{2}{3}$  percentage points compared to the normal time baseline case. In particular, the joint shock intensifies the effects of climate change for extremely intense typhoons. For 25-year return period events, the effects of climate change remain small (the difference of the impact of a 25-year return period event in the current and future scenarios). However, for 500-year return period event, the difference between current and future scenario with the pandemic rise to 4 $\frac{1}{2}$  percentage points compared to one percentage point difference under normal time baseline.

**The exercise and results should be interpreted with caution and considered as exploratory, given the significant uncertainty over scenarios and models.** Stress tests for climate change-related risks face multiple layers of enormous model and scenario uncertainties. In many cases, the

uncertainties are not quantifiable. For example, it is impossible to put probability distribution over multiple global climate scenarios (i.e., Representative Concentration Pathways) as they depend substantially on human behavior, policies, and economic and population growth in addition to physical dynamics in nature. Such severe uncertainties are called “deep” uncertainty or ambiguity. Under such uncertainties, it is not appropriate to attempt drawing strong prudential policy implications based on a small exercise.

**At this stage, the Philippine authorities should conduct more exploratory work to examine the potential impact of climate change with more granular data.** As for physical risk, inter-agency collaboration, including non-economic agencies such as Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA), Department of Energy (DOE) and Department of Agriculture (DA), is critical. As for transition risk, the risks seem to be coming from the power generation sector and the need to rebalance their long-term energy plans to shift from coal-based power plants to renewable sources, which could accompany electricity price increases. As for the banking sector data, the Bangko Sentral ng Pilipinas (BSP) should increase the granularity of the exposure data by industries and locations. Also, further strengthening the disclosure requirements could enrich firms’ and financial institutions’ exposures to climate change risks. Such information would be helpful to identify more micro-level channels of the linkages between climate change and financial stability. The issue of deep model and scenario uncertainty should be taken into these works explicitly, and a variety of models and scenarios could be considered. The FSAP exercise could be considered as one of the first steps to do so.

<b>Table 1. Recommendations<sup>1</sup></b>		
<b>Recommendation</b>	<b>Timing<sup>2</sup></b>	<b>Agency</b>
<b>Addressing Resilience, Integrity, and Effectiveness</b>		
<b><i>Climate Change, Environment Risks and Supervision</i></b>		
Perform in-depth environmental risk assessments on banks and insurers	MT	BSP, IC
Improve information collection, monitoring of risk metrics, and stress test capacity for climate and environmental risks.	MT	BSP, IC, government
Issue detailed guidelines on environmental risk management, stress testing and disclosures.	MT	BSP, SEC
1/ Recommendations included in this table should be considered high priority without exception. Additional recommendations in the various FSAP topic areas are included in the corresponding Technical Notes.		
2/ Short-term (ST) = within one year; medium-term (MT) = one to three years		

## INTRODUCTION

1. **Globally, there is increasing attention to the impact of climate change on financial stability.** Regulators and central banks—amongst others through the Network for Greening the Financial System (NGFS)—have started to warn of the impact of climate change and environmental risks on the stability and soundness of financial sectors. These calls follow attention on this topic by the Financial Stability Board (FSB) Task Force on Climate-Related Financial Disclosures and G20 Green Finance Study Group. In this context, the Global Financial Stability Reports (GFSRs) have started to discuss financial stability and climate change. The [October 2019](#) issue reported incorporating environmental, social, and governance (ESG) principles to finance. The [April 2020](#) report looked at the impact of physical risks from climate change on global equity valuation.
2. **Financial stability risks from climate change can be broadly categorized as either physical or transition risks.** Physical risks originate from weather-related phenomena that can lead to loss of physical capital, economic growth, and financial assets. Examples are natural catastrophes, including typhoons, floods, and droughts, as well as gradual changes in sea-level, temperature, and precipitation. Economic and financial losses can either be insured, leading to losses for insurance companies, or uninsured, which means that losses are directly felt on other corporate, household, and government balance sheets. Transition risks are related to economic adjustment costs during the transition towards a carbon-neutral economy. Major drivers of transition risks include public policy (e.g., carbon pricing and regulation), technological development, and changing consumer behavior.
3. **The vulnerability of an economy to climate change is country specific.** For physical risks, much of which depend on the geographical location of businesses and other assets, as well as climatological developments over time. Elevated risks are found in coastal areas, areas that are highly prone to hurricanes or typhoons, and areas that are close to the equator (McKinsey, 2020). Over time, climate change will shift the probability distribution of natural catastrophes and other weather-related phenomena, often increasing the economic losses from these events depending on economic development and adaptation. In general, lower-income countries tend to be more vulnerable to climate change while having less capacity to deal with its consequences ([World Economic Outlook October, WEO, 2017](#), Feyen et al. 2020). For transition risks, vulnerability depends on the structure of the economy, the level of country development, and how far it is from achieving global goals to reduce green-house gas emissions such as the Paris Agreement.<sup>2</sup>
4. **The Philippines is highly vulnerable to physical risks from climate change (Table 2).** As discussed in the [2019 IMF Article IV](#) report and the World Bank's Technical Note (TN) on climate change, the Philippine economy is categorized as one of the world's most vulnerable economies to climate change and weather-related natural disasters. In particular, it is situated in the world's most typhoon-prone region, experiencing 20 typhoons per year on average. All major cities and most of

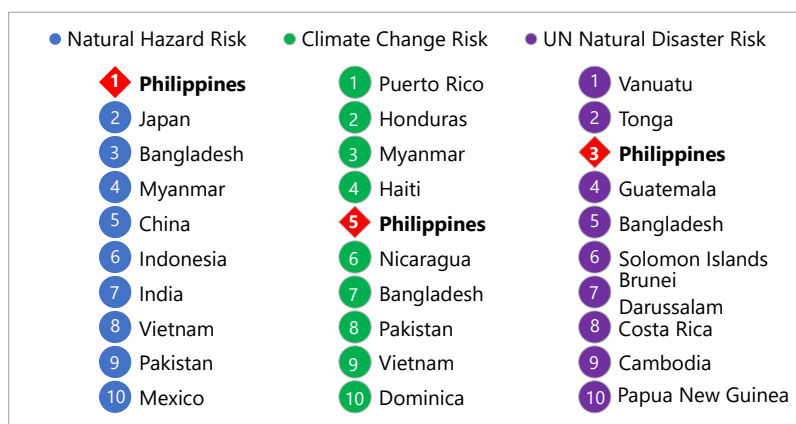
<sup>2</sup> For instance, Climate Action Tracker keeps track of governments' actions to counter climate change and classify economies depending on how far they are from achieving the Paris Agreement.



the population reside on the coastline, including the metropolitan Manila area where about 60 percent of economic activities take place. The 2019 [Inform Global Risk Index](#)<sup>3</sup> ranks the Philippines as the most susceptible country to climate change-related hazards. Similarly, the [Global Climate Risk Index](#)<sup>4</sup> 2019 ranks it as the fifth most vulnerable to the physical risk from climate change and the fourth most affected country by extreme weather events for the period 1998-2017. Also, typhoons are the largest source of economic loss due to its geographical location in the Philippines, which is also subject to earthquakes and other natural disasters.

**5. The climate is already changing across many parts of the Philippines, further amplifying damages.** Temperatures are rising, increasing seasonal rainfall have been observed in many parts of the country, and sea levels are rising at nearly double the global average rate, worsening storm surge impacts [Department of Science and Technology (DOST)-PAGASA, 2018]. In the past 65 years, the frequency of all tropical cyclones has decreased slightly, but more powerful typhoons have been observed. These trends in typhoon frequencies and intensities are expected to continue in the future. Given the non-linear relationship between storm intensities (windspeed) and damages to physical capital, this suggests that economic losses from typhoons could increase significantly in the future.

**Table 2. Philippines: Countries with High Natural Hazard and Climate Risk**  
(Ranking 1 to 10; 1 means the most vulnerable)



Source: 2020 Philippines Article IV Staff Report.

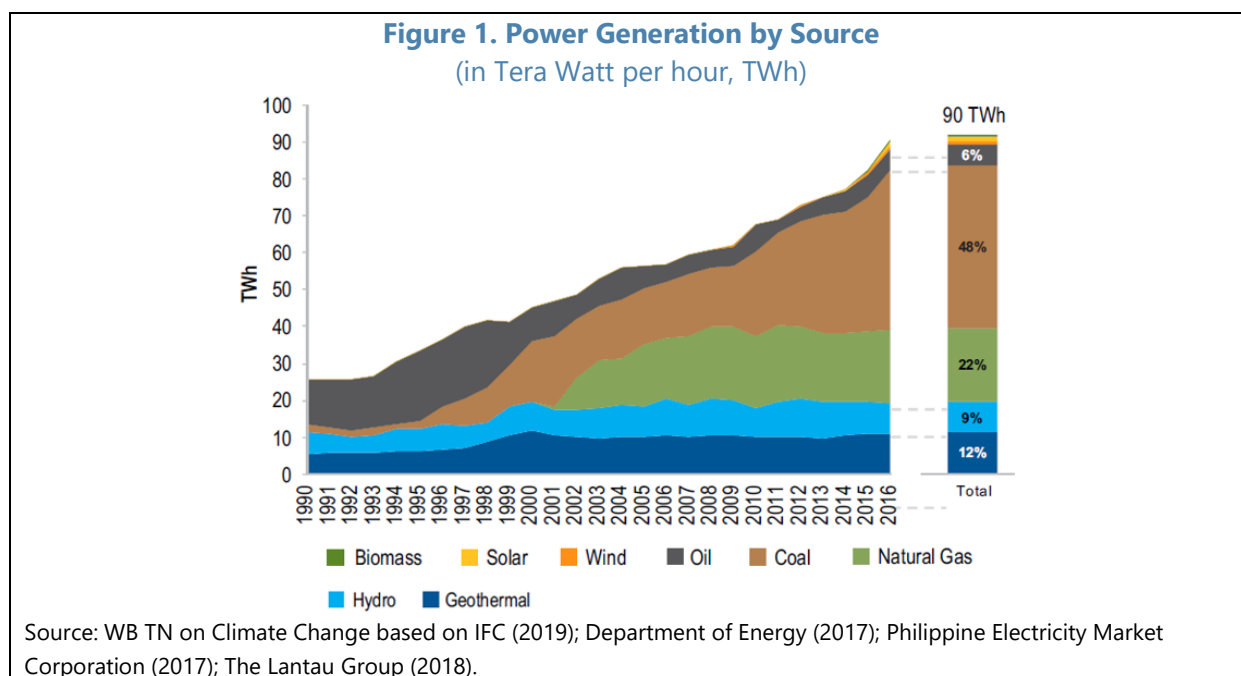
**6. Existing studies also suggest the importance of disaster risks to banks in the Philippines.** The WB's climate change TN found that typhoons increased bank's nonperforming loans (NPLs) historically. A study by the Bangko Sentral ng Pilipinas (BSP) examined the relationship

<sup>3</sup> INFORM is a global initiative of UN organizations, the European Union, and other civil society as well as academic actors to provide open-source risk assessments for humanitarian crises and disasters. The initiative has developed and later expanded the INFORM Global Risk Index, which combines 50 indicators to measure hazards and people's exposure to them, their vulnerability, and the resources available to help people cope.

<sup>4</sup> Germanwatch publishes the index, analyzing how countries and regions have been affected by the impact of weather-related events such as storms, floods, and heatwaves.

between regional rainfall data and bank performance indicators at branch levels.<sup>5</sup> It found that, following extreme rainfall events, loan growth and asset quality deteriorated, and deposits were withdrawn.

**7. Exposures to transition risk are also relevant and appear to be concentrated in the coal-based power generation sector.** According to [Climate Action Tracker](#), the Philippines' current policies are not entirely consistent with the long-term temperature goal of the Paris Agreement as of end-2020, while it is consistent with the 2009 Copenhagen 2°C goal. Given the importance of securing energy supply for the fast-growing economy, the share of coal-based power generation increased from a negligible amount in the 1990s' to nearly 50 percent in 2016 (Figure 1) as they are more affordable than other power sources. To achieve the Paris Agreement target, more policy action will be needed, including the implementation of the moratorium on new coal-based power plants announced by the Department of Energy in late 2020 ([Ahmed and Brown, 2020](#))



**8. This FSAP focused on the risk assessment of physical risks primarily because there are substantial existing studies that facilitate the analysis.** While the Philippines' current policies are still short of achieving the Paris Agreement, the country appears to be better placed to achieving the goal than advanced economies and several large emerging market economies that are well below achieving the 2009 Copenhagen 2°C goal ([Climate Action Tracker](#)). Moreover, given the frequent typhoons, there exist substantial research on the implication of global warming to typhoons in the Philippines and their expected damages to infrastructure. These studies allow to construct tailored physical risk scenarios based on solid science.

<sup>5</sup> "The impact of extreme weather episodes on the Philippine banking sector—Evidence using regional branch-level data" by Bayangos, Augusto, and Del Prado (2019).

**9. The exercise focused on solvency of banks.** Banks dominate the Philippines' financial system. The insurance sector, especially the catastrophe insurance market, is underdeveloped partly due to the limited technical capacity of the insurance regulator. Moreover, the impact on insurers is generally expected to be small because they adjust premiums annually. If climate change increases disaster risks significantly, insurers can immediately raise premiums to limit the impact on their capital and profitability. Then the cost of climate change will fall on consumers who cannot afford higher premiums or on the public sector if governments provide subsidies to make insurance affordable.<sup>6</sup> Therefore, the prominent linkages between financial stability and climate change lie in the banking sector.

**10. Against this backdrop, the FSAP developed a new macro-scenario stress testing method for banks to assess physical risks from climate change.** The main innovation of this exercise is the approach we used to construct scenarios. Scenarios consist of three sub-components: climate, disaster, and macrofinancial scenarios. The climate scenario is based on an existing study by the Government of the Philippines. It takes a high emissions global climate scenario—expressed as Representative Concentration Pathways (RCP) of greenhouse gas (GHG) emission and global temperature depending on carbon emission policies and technological advancement—from the Intergovernmental Panel on Climate Change (IPCC). Then, it estimates how the distribution of typhoons (frequency and intensity measured by windspeed and precipitation) changes in the Philippines by the mid-21<sup>st</sup> century for a given global scenario. The disaster scenario is based on the WB's catastrophe risk model for the Philippines and translates the impact of typhoons on the loss of physical capital. The macrofinancial scenario uses a DSGE model calibrated for the Philippines and calculates the impact of lost physical capital on the economy. Then, we estimate the impact on bank solvency using the same approach for macro scenario stress tests for banks.

**11. The literature on stress testing for climate change risk is rapidly growing, especially on transition risks in advanced economies (AEs).** In 2020 alone, the NGFS published several guidance notes on how to incorporate climate change in financial stability analysis and supervision (NGFS, 2020a, 2020b, 2020c). Climate risk stress tests have so far mostly focused on transition risks in advanced economies such as Battiston and others, 2017; UNEP-Oliver Wyman 2018, Vermeulen and others, 2019; Reinders and others, 2020. Some central banks have also completed or initiated climate risk stress tests to investigate transition risks (DNB, 2019; BoE, 2019). [2020 Norway FSAP](#) considered the impact of carbon price increases as well as a forced reduction in Norwegian oil output on nonfinancial firms, macroeconomy, and then banks.

**12. On the other hand, there has been a relatively limited number of stress tests of banks for physical risks.** Catastrophe risk (CAT) model-based exercises are well established to gauge the impact on insurers' liabilities (e.g., Lloyds, 2014). But incorporating the effects of long-term climate change is not standard practice yet. Also, the applications to emerging markets and developing

---

<sup>6</sup> More broadly, climate change could give a wide range of impact on broad economic activities, inequality, health, and mortality among others (IPCC 2014), which is not included in our exercise.

economies (EMDEs) banks are limited.<sup>7</sup> Existing exercises for banks are mostly disaster stress tests that do not explicitly incorporate disaster distribution changes under a global climate scenario. A DNB's work (DNB, 2017) performed a partial top-down scenario analysis for dyke breaches in certain regions. [2019 Bahamas FSAP](#) considered the impact of hurricanes, assuming a historically observed hurricane scenario. A project by UNEP-Acclimatise (2018) conducted bottom-up exercises with several global banks. While it considered the change in disaster event distributions in a certain global climate scenario, it focused on a couple of specific exposures.

**13. This FSAP developed a new macro-scenario physical risk stress test for banks in an emerging market, providing a unique contribution to the literature.** To our knowledge, we are the first to link typhoon CAT models to macro scenario stress tests of banks. CAT models consider extreme tail events such as once in 100, 250, and 500 years events (called return periods in the insurance industry), which is a standard practice in the insurance industry.<sup>8</sup> Disaster risk scenarios based on historical observations tend to be much more moderate than those considered in CAT models since recorded history is usually much shorter than 250 or 500 years. For instance, category five that hit the Philippines in 2013 was one of the most powerful tropical cyclones ever recorded, but it was still a once in 30-year event in terms of losses because it affected mostly rural areas. Using historically observed probability distributions to estimate losses is likely to underestimate disaster risk (AIR, 2017). Furthermore, we explicitly account for climate change effects by considering both current disaster risks and the potential future development of this risk under a chosen climate scenario. This approach contrasts with standard CAT models—catastrophe insurance contracts are usually set annually, so insurers do not need to consider the evolution of disaster risks far in the future due to climate change. Accounting for climate change requires working with climate science models that translate global scenarios to country-specific disaster risks. We relied on a study by the Government of the Philippines to construct future disaster risks.

**14. Similar to other pioneering works, our climate change stress test is subject to significant uncertainties and limitations.** Stress tests for climate change-related risks face multiple layers of model and scenario uncertainties as well as limitations with existing tools.

- **Uncertainties from climate models:** There is a wide range of globally accepted climate scenarios that show different GHG emissions trajectories over time (Rogelj and others, 2018). While the green-house gas' role in global warming (green-house gas effects) is qualitatively well established (IPCC, 2014), the exact quantitative effects depend on various other factors (such as land use, the share of areas covered by ice, and so on). There is climate science model

<sup>7</sup> CAT risk models for EMDEs are much less developed than those for AEs. While the humanitarian and economic impact of disasters could be very severe in EMDEs, they are little covered by insurance as the markets are underdeveloped, limiting demand for such models. Also, the dollar value of disaster-related losses is much higher in AE, reflecting purchasing power differences and property valuations, among others. For instance, all of [Lloyds' mandatory Realistic Disaster Scenarios](#) for disaster risk stress tests are flood, windstorm, earthquake, and terrorism risks in the US, Europe, and Japan.

<sup>8</sup> Return period (the inverse of frequency) of 100 years is often used for pricing disaster insurance. 200 years could be used for technical reserve adequacy, and 500 years could be used for examining the risks to the reserves. The term "return" is used since it shows the period before the next disaster "returns."

uncertainty about the precise effects of global warming on local climate-related phenomenon (e.g., temperature, precipitation, sea-level rising, and natural disasters) at a country and regional (within a country) level. Also, there is high uncertainty about potential tipping points in the global climate system, some of which may yet be unknown (Good and others, 2014).

- **Limitation of catastrophe models:** Our exercise focused only on risks to physical capital from typhoons and did not include the broader physical risks from climate change due to the limitation of CAT models. They were originally designed to serve property insurers and typically handles only typhoons and floods and each at a time, following the insurance market practice. The damages are measured by the value of destructed buildings and infrastructure. Other types of models are needed to gauge the damages from sea-level rising, drought, heatwave among others. Relevant measures for various damages will also be different for other risks—for example, harvest losses for drought and health and human life costs for heatwave. Also, typical CAT models do not consider the changes in disaster frequencies in the future due to climate change since property insurance costs are usually annual. The accuracy of the simulation-based CAT model depends on, among others, the data on physical capital (buildings and infrastructure) location and value, which could contain a significant margin of error in EMDEs where disaster insurance coverage is scant.
- **Macrofinancial impact of disasters:** The step of translating the physical capital losses to macrofinancial impact is also subject to substantial model uncertainties. Our exercise took a macro scenario approach, which can capture general equilibrium effects well but lacks precision at the sectoral and regional levels. It contrasts with a micro-level approach, that, although it remains a partial-equilibrium approach, focuses on a couple of key channels.

**15. Therefore, our exercises emphasize the range of possible outcomes rather than point estimates.** Some of these uncertainties that we cannot even put subjective probability over potential outcomes are called “deep” uncertainty or ambiguity. Standard uncertainty embedded in general equilibrium model-based macroeconomics is not deep. Agents know the economic structures and possible future states and can put probability over them. Then they choose optimal actions to maximize their expected utility or returns. In contrast, deep uncertainties are a severe form of uncertainty that cannot be quantified (see Lempert and others, 2013, for example). For instance, it is hard to put probability distribution over future climate scenarios like RCPs. Under such uncertainties, some climate scientists have been exploring alternatives to the “predict-and-act” decision-making framework to choose long-term adaptation and mitigation policies that have small vulnerabilities in case the future turned out to be very different from what was expected. One of the typical approaches to handle such uncertainty is scenario analysis, including stress tests. Producing a range of outcomes based on alternative scenarios and key parameter assumptions helps to avoid having a false sense of security from possibly moderate average outcome.

**16. Given these uncertainty and limitations, our climate change stress test does not aim to be used for prudential regulation discussion.** It is the first step to incorporate climate change risks in the stress testing of banks in the Philippines. These analyses are explorative and are mainly aimed to inform academic and broad policy discussions on climate change, in contrast to more traditional

stress test exercises that ends with prudential policy discussions (such as increasing capital and liquidity buffers). Thus, the policy recommendations are mostly about expanding the data, enhancing disclosures, and strengthening the capacity to analyze financial stability risks associated with climate change.

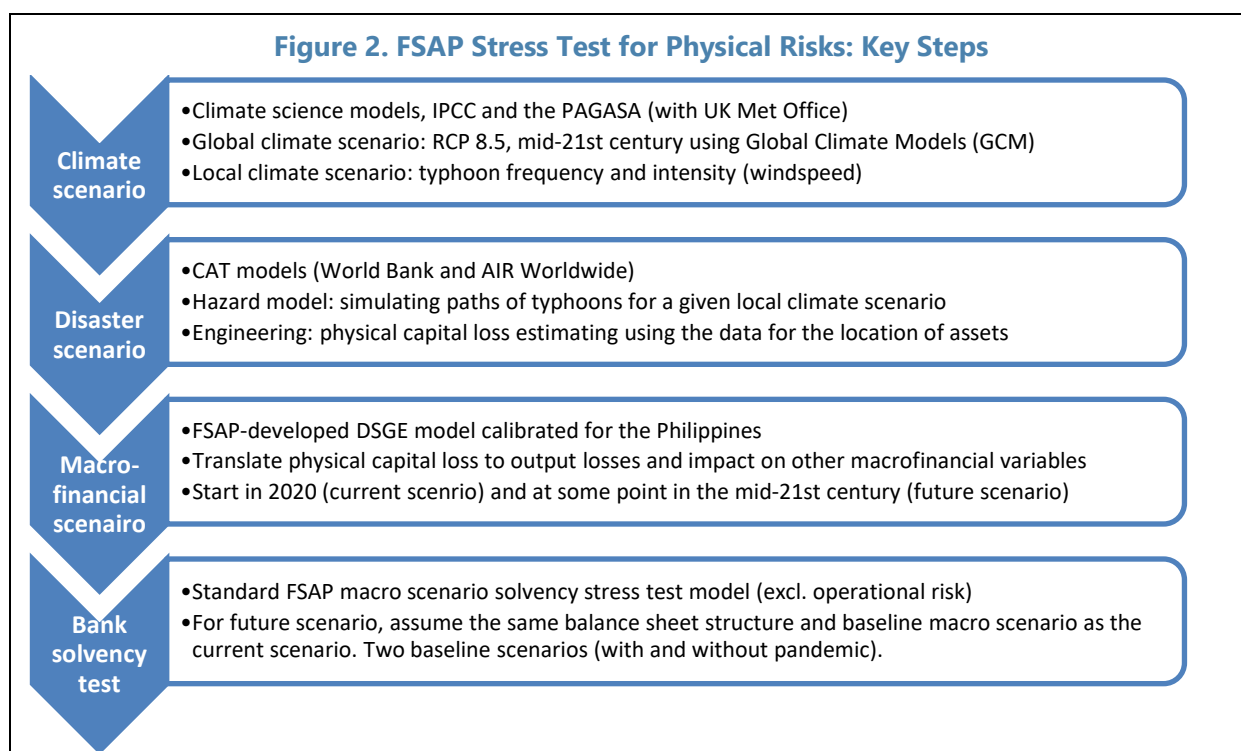
## CLIMATE CHANGE STRESS TEST

### A. Overview

**17. Stress testing for physical risks requires multi-disciplinary collaboration.** As shown in Figure 2, there are four key steps in the FSAP stress test for climate change: 1) climate scenario, 2) disaster scenario, 3) macrofinancial scenario, and 4) bank solvency stress test. The last two steps are within standard FSAP work. However, building climate and disaster scenarios requires meteorological, climate science, and CAT risk modeling expertise, which is outside of the typical FSAP members' skills. Therefore, this FSAP collaborated closely with World Bank experts from the Disaster Risk Financing and Insurance (DRFI) Program that have developed a CAT risk model for the Philippines with technical support from a consulting company on CAT models ([Air Worldwide](#)). As for the climate scenario, we relied on the 2018 study by the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA) in collaboration with UK Meteorological (Met) Office (documented in Gallo and others, 2018). See Annex I Stress Test Matrix (STeM) for a more detailed summary.

**18. The scenarios consider climate change through its impact on typhoons' windspeed, but not the other channels, due to the limitations of climate and CAT risk models and the scope of PAGASA's study.** Existing weather-related CAT models typically cover the destruction of physical capital from either wind or flood, not both, given the practice of catastrophe insurance. Also, other channels that are not insurable or are covered by different types of insurance are not considered in CAT models, such as health and life risks from the heatwave and the risks to agricultural outputs from drought and other weather conditions.<sup>9</sup> The PAGASA's exercise provides the probability distribution of storm frequency, intensity, seasonality, and spatial density today and the projected changes at the mid-century (2036–2065) specifically for the Philippines. As for intensity, they consider only changes in windspeeds and not changes in storm surge (e.g., due to sea-level rise) or precipitation from storms, which require different types of climate models. As a result, the disaster scenarios quantify direct physical capital losses from typhoons' wind (the value of lost infrastructure in percent of existing physical capital stock), but not floods. Therefore, our scenarios cover only a part of the physical risks of climate change.

<sup>9</sup> For agricultural output, there is a different class of model (crop model) that examines the relationship between global climate conditions to crop yields. See, for instance, Nelson and others (2014) who used global climate models to produce future climate variables (e.g., temperature and precipitation), which were then put into biophysical models (global gridded crop models) to simulate crop yield effects. These, in turn, became input into economic models (computable general equilibrium, CGE, models often used in the literature of climate economics as well as partial equilibrium models specialized in agriculture) to simulate economic impact.



**19. Both the impact of extreme weather events and incremental events are considered, but solvency tests focus on extreme events.** Physical risks materialize as rare tail events that could reduce capital or cause incremental changes through more likely but less destructive typhoons, which could be profitability events. While disaster risk management literature tends to focus on tail events, incremental changes could also be relevant by reducing certain sectors' average profitability and banks exposed to these sectors. Therefore, we considered the impact of extreme events—shown as the impulse responses of macrofinancial variables to enormous capital stock losses—and incremental changes—expressed as the reduction of steady-state economic growth rates. However, it turned out that the steady-state impact was very small compared to the baseline potential economic growth rate of the Philippines. Therefore, the bank solvency stress test focused only on tail risks.

**20. We took the macrofinancial scenario approach instead of the industry- or firm-level scenario approach because of data constraints and investigating potential systemic risks.** An example of the industry- and firm-level exercise is UNEP-Acclimatise (2018), where banks implemented bottom-up stress tests using granular internal data under the guidance of UNEP and Acclimatise. The exercise focused on two specific channels. The first is credit risks from the exposures to the agriculture and energy sector as climate change lowers their productivity and revenues. The second is the impact on loan-to-value (LTV) ratios of property loans as collateral properties are damaged. The BSP collects bank loan data by industries and branch-level data (both from 2014),<sup>10</sup> but not by industry and location. Also, the BSP does not collect LTV ratio information

<sup>10</sup> Branch-level data may not be the same as consolidated data by location for each bank since some of the exposures to region A could be booked at region B (e.g., at the headquarter in Manila).

for any types of credits, including property loans, as it does not use LTV as a prudential tool.<sup>11</sup> Therefore, the micro-level and approach that needs more granular information was not feasible. At the same time, the macro-scenario approach focuses on systemic weather events that cause economy-wide impact, which is the main interest of FSAP stress tests. The DSGE model also incorporates general equilibrium effects that are not considered in UNEP-Acclimatise (2018) and macrofinancial effects (the model includes the financial sector).

**21. We developed a Philippines-specific DSGE model to account for physical capital losses explicitly, instead of Global Macrofinancial Model (GFM) often used in FSAPs.** Since CAT risk models produce the value of lost physical capital stock in percent of existing capital, a straightforward way to incorporate these damages to macro models is to interpret the damage as a capital depreciation shock. The GFM does not have such shocks, as it focuses on multi-country real and financial spillovers and various types of macrofinancial linkages. Therefore, we developed a simplified single country DSGE model with capital depreciation shocks and adjustment costs to rebuild capital and parameters calibrated using historical data of the economy.

**22. The bank solvency tests examined the effects of tail weather events for three years upon disasters that would occur in 2020 and sometime in the mid-21<sup>st</sup> century.** A typhoon that causes large economic damages hit the economy in the first quarter of the projection period, followed by recovery (no more additional tail disasters). Following the macro scenario stress testing approach discussed in the stress testing TN and summarized in Annex I, the stress test horizon is 3-years upon a disaster. Since the country already faces disaster risks under current climate conditions, the effect of climate change should be measured as the difference between the impact implied by the current and future probability distribution of typhoons. For this purpose, we considered “current scenarios” that start in late 2020 and “future scenarios” that take place at some point in the mid-21<sup>st</sup> century. The bank balance sheet and baseline economic projections in the future scenarios are assumed to be the same as 2020 to identify the marginal effects of climate change, keeping other conditions equal. For each disaster scenario, we examined three sub-scenarios—baseline without disaster and with once in 25- and 500-years disasters—in order to highlight the range of possibilities rather than point estimates.

**23. For both current and future scenarios, we considered two baselines, scenarios with and without the pandemic.** In the literature of broader tail risk management, there has been increasing interest in “compound risks,” where multiple tail events materialize within a short period of time and causing cascading effects. Even within the CAT risk literature, models usually focus on a single tail event a year instead of multiple events. While the importance of multiple disasters is recognized well, such a phenomenon has very low ex-ante probability and complicates models substantially. The compound risk literature considers several types of risks, including economic, climate and environmental, geopolitical, social, and technological risks. The COVID-19 highlighted the importance of compound risk. Given that the pandemic has already materialized, the likelihood of

<sup>11</sup> The LTV at the time of loan origination is used to categorize loans to secured (LTV ratio of above 60 percent) or unsecured, which are subject to different provisioning rules.



double tail risk—pandemic and disaster, for example—has jumped enormously. In order to identify the possible cascading effects, our exercise considered both single disaster risk using pre-pandemic forecast (January 2020 WEO) and compound risk with pandemic using October 2020 WEO that incorporates the effects of COVID-19.

**24. Following the standard FSAP practice, our bank solvency test does not account for operational risks from disasters.** In reality, disasters are likely to disrupt bank business operations. If a typhoon destroys branch offices or ATMs, it will take some time before restoring retail services. If financial market infrastructure, like a payment system, is knocked down, the whole banking system would be affected. In order to assess the impact of such disruptions on bank solvency accurately, one would need more detailed information on banks' contingent planning and insurance for disruptions.

## B. Climate Scenario

**25. The PAGASA's exercise assumes one of the several standard global climate scenarios—the high-emission scenario (RCP 8.5) that is more likely to increase physical risks than the other scenarios.** RCPs, developed by the IPCC, describe four different 21<sup>st</sup>-century pathways of GHG emissions, its atmospheric concentrations, air pollutant emissions, and land use. Key factors contributing to the change in human caused GHG emissions are economic and population growth, lifestyle and behavioral changes, associated changes in energy and land use, and technology and climate policy. In the fifth Assessment Report (AR5) by the IPCC (IPCC, 2014), there are four RCPs: a stringent mitigation scenario (RCP 2.6), intermediate scenarios (RCP4.5 and 6.0), and one with very high GHG emissions (RCP 8.5).<sup>12</sup> RCP2.6 represents a scenario that aims to keep global warming likely below 2°C above pre-industrial temperatures at end-21<sup>st</sup> century. RCP 8.5 is the “business as usual” scenario without climate change policy, leading global temperatures by 2100 to 4.0-6.1°C above pre-industrial levels. Since physical risks tend to rise in high emission and temperature scenarios, RCP8.5 is appropriate for our purpose. In a stringent mitigation scenario, physical risks are not likely to increase, but transition risks are.

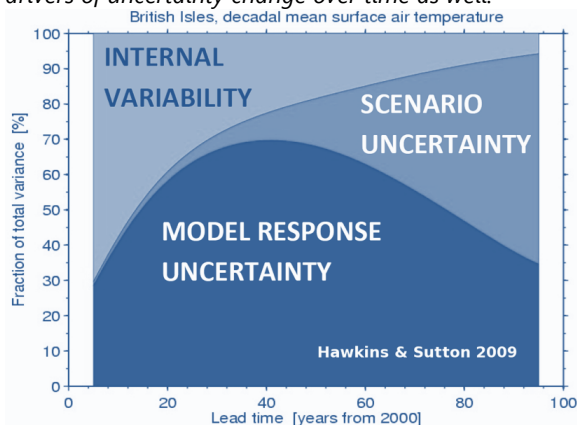
**26. However, it should be noted that climate model uncertainty dominates over climate scenario uncertainty for the mid-21<sup>st</sup> century considered in the PAGASA's work.** There are substantial uncertainties over global climate projections. Uncertainty over climate projection increases towards the end of the 21<sup>st</sup> century, driven by changing key drivers (Hawkins and Sutton, 2009). During the first couple of decades, internal variability (e.g., chaotic factors that drive day-to-day or periodic weather variations) is the key driver. By mid-century, the difference of projections across climate models becomes the main source of uncertainty. Only towards the end of the century, the difference across scenarios starts to dominate. In the mid-21<sup>st</sup> century, which is the

<sup>12</sup> See the [CarbonBrief article](#) for less technical descriptions of RCPs. RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in absence of climate change policies.

focus of PAGASA’s work we use, the difference between our scenario (RCP 8.5) and the others are small and largely explained by climate model uncertainties.

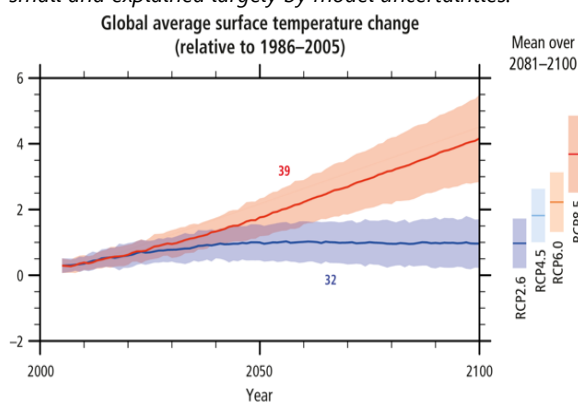
**Figure 3. Uncertainty in Global Climate Projections**

Panel 1: *Uncertainty increases over time, and the main drivers of uncertainty change over time as well.*



Source: Hawkins and Sutton (2009).

Panel 2<sup>1</sup>: *In mid-21<sup>st</sup> century, difference between RCPs is small and explained largely by model uncertainties.*



Source: IPCC Fifth Assessment Report (AR5, 2014).

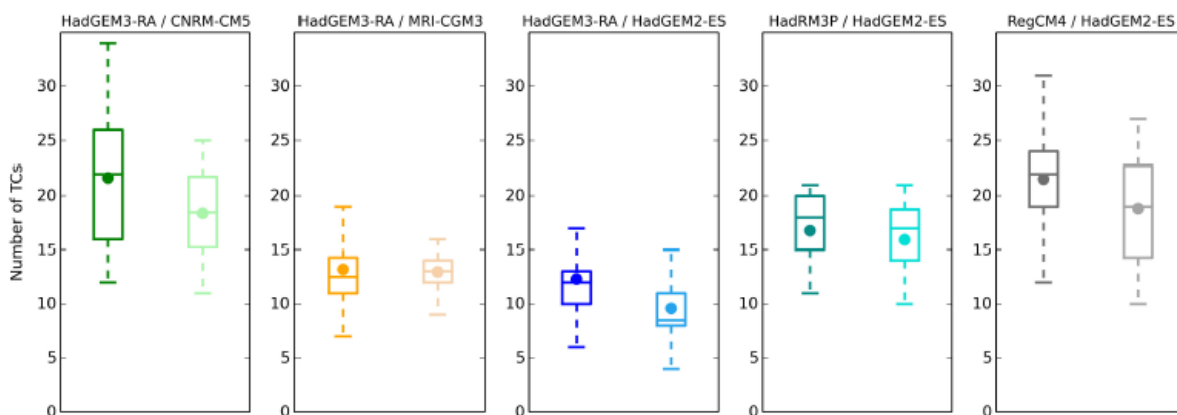
1/ Blue and red lines and shading denotes the mean and 5-95 percentile range, based on simulations from 32 climate models for RCP 2.6 and 39 models for RCP 8.5. RCP 8.5 is a very high emission scenario representing the 90<sup>th</sup> percentile of no-policy scenarios available as of the AR5 publication. RCP 2.6 is a scenario with substantial mitigation policies aiming to limit the increased of global temperature to 2°C in the 21<sup>st</sup> century.

**Figure 4. Uncertainty in Climate Change’s Impact on Typhoon Characteristics in the Philippines<sup>1/</sup>**

Most models predict the frequency of typhoons are likely to decline in the future in the Philippines.

**Panel 1: Annual tropical cyclone (TC) frequencies produced by the five climate models.**

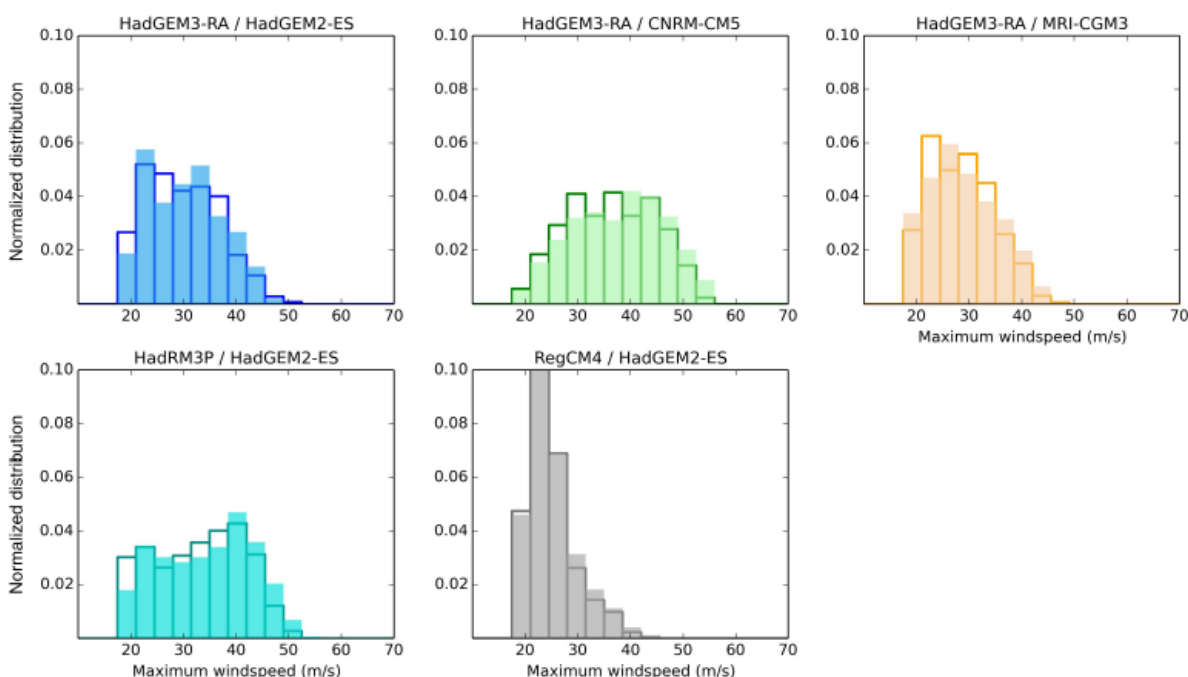
Historical (1971-2005) period (left) and future (2036-65) period (right) for the five climate models. The box limits correspond to the 25<sup>th</sup>-75<sup>th</sup> percentile and the whiskers describe the range of values. The middle line of the box shows the median and the circle indicates the mean of the simulation results.



Three models produce significantly different intensity distributions with small increases of means, except for two models (HadGEM3-RA/CBRN-CM5 and HadRM3P/HadGEM-2ES) that project a significant increase.

**Panel 2: Distribution of maximum intensities measured by maximum sustained wind speeds of tropical cyclones**

Historical (1971-2005) period (lines) and future (2036-65) period (full colored bars)



Source: Gallo and others (2018) Figures 8 and 9 that documents the details of the 2018 PAGASA exercise.

1/ The exercise used three global climate models HadGEM-2ES (developed by the UK Met Office Hadley Centre), CNRM-CM5 (developed by the Centre National de Recherches Meteorologiques, CNRM, in France), and MRI-CHCM3 (developed by the Meteorological Research Institute, MRI, in Japan). HadGEM3-RA, HadRM3P, and RegCM4 are downscaling models to provide Philippines’ specific projections based on the global climate models.

**27. PAGASA’s climate change projections for the Philippines suggest that there likely to be, on average, fewer but slightly more “intense” typhoons in the future.** The exercise evaluated the impacts of climate change on typhoon characteristics under the global scenario—implying the global temperature increase of roughly 1.4 to 2.6°C above 1986–2005 levels—under five Regional climate and Global circulation models<sup>13</sup> (RCM and GCM) simulations (see Gallo and others, 2018). Three of the models suggest significant decreases in tropical cyclone frequency (two suggest little change). Four of the models agree on a projected increase in tropical cyclone “intensity”—measured by the maximum sustained windspeed—overall, with two showing significant increases. In all scenarios, year-to-year variability will remain high. This result is consistent with IPCC’s findings for the Western North Atlantic (IPCC, 2014), which concludes it is “more likely than not” that intensities will increase.<sup>14</sup>

**28. Similar to the global climate projections, we should keep in mind that there is enormous model uncertainty.**<sup>15</sup> According to Gallo and others (2018), existing studies found that while GCMs could be useful to infer annual average typhoon numbers globally, there is low confidence in their geographical distribution at the ocean basin level. To obtain more accurate projections for a country, one would need to “downscale” (i.e., translate) the GCM outputs to region specific impact using a Regional Climate Model with higher resolution (i.e., projection per smaller square km/ft grid cells). The PAGASA’s 2018 exercise consisted of the following three steps; 1) select appropriate GCMs that can simulate key typhoon characteristics relevant for the Philippines, 2) downscale global models for the country, and 3) validate the models by comparing simulation results with historical data.<sup>16, 17, 18</sup> As shown in Figure 4, the five models show substantially different results, especially regarding the intensity of typhoons.

<sup>13</sup> Global Climate Models are also called as General Circulation Models, which simulate the physics of the climate itself, capturing the flow of air and water in the atmosphere and/or oceans as well as the transfer of heat. The RCM “downscales” the low-resolution global climate forecast specifically to the Philippines at higher 10-25 km<sup>2</sup> resolution.

<sup>14</sup> The IPCC uses specific languages to express likelihood. For example, “likely” is used for outcomes that could occur with a probability of 66-90 percent. “More likely than not” means outcomes that occur with a probability of 50-66 percent.

<sup>15</sup> See, for example, the [article](#) on CarbonBrief for the basics of climate models.

<sup>16</sup> GCMs are developed, maintained, and improved by over two dozen scientific institutions worldwide, with each center often building several models at the same time. Models are usually named after the center themselves, such as the “[HadGEM3](#)” family of models developed by the UK Met Office Hadley Centre.

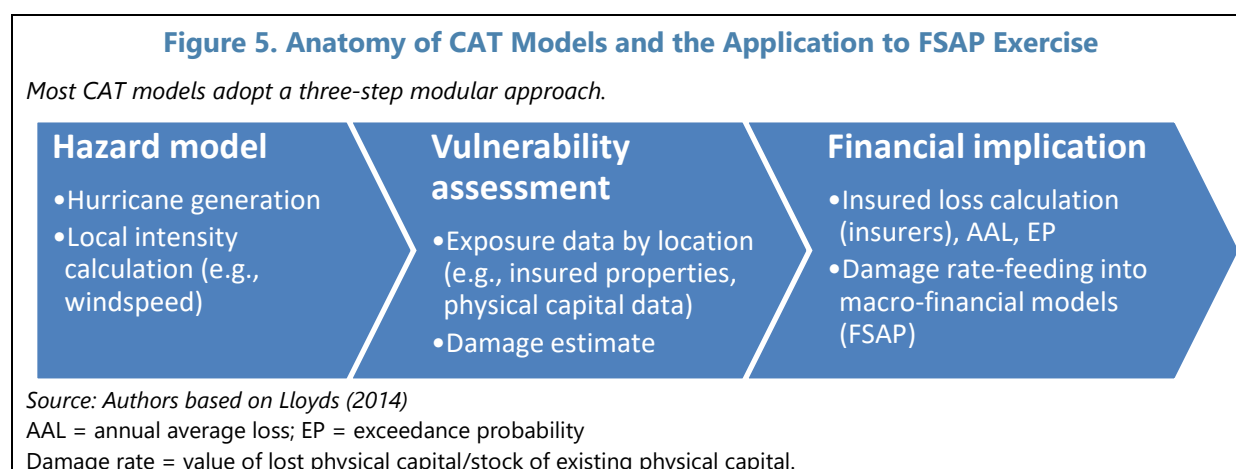
<sup>17</sup> The climate modeling community is much more concentrated than, for instance, the macroeconomic economic modeling community partly because of large capital investment needs. A GCM typically contains codes to fill 18,000 pages of printed text, hundreds of scientists for many years to build and improve, and a supercomputer with the size of a tennis court to run.

<sup>18</sup> There are a number of climate models developed by various research institutions, some of them are similar but not the same. Therefore, climate scientists conduct cross-model comparison exercises called the [Coupled Model Intercomparison Project](#) (CMIP) once every five years or so. The exercise set the same data and key simulation parameters for each model to run so that differences in the results reflect the model differences rather than differences of simulation design and data. It is structured in a similar manner as the Basel bottom-up exercises to compare banks’ internal rating models to see the variations of risk-weighted assets for the common hypothetical portfolios ([Basel Committee on Banking Supervision, regulatory Consistency Assessment Programme, 2013](#)).

## C. Disaster Scenarios

**29. Catastrophe modeling, based on the science of natural hazard, was commercialized in the late 1980s originally for managing property insurance risks (Lloyds, 2014).** Standard actuarial techniques (based on expected mean values) in the insurance industry are not appropriate to estimate catastrophe losses (i.e., losses upon tail events) because historical loss data are scarce, especially for low-frequency high-impact events that could threaten insurers' solvency. The models were widely accepted in the industry upon US Hurricane Andrew in 1992, highlighting deficiencies in the purely actuarial approach to quantify CAT risk losses. Three commercial vendors provide globally recognized CAT risk modeling software, Air Worldwide, Risk Management Solutions (RMS), and EQUecat, now owned by CoreLogic.

**30. Most CAT models adopt a modular approach (Figure 5).** The hazard module simulates numerous target hazards (e.g., hurricanes or floods) based on the scientific models and the present state of natural forces (e.g., ocean temperatures). For hurricanes, the module produces the number of hurricanes in a year and their intensity (windspeed). The vulnerability module incorporates the exposure data (i.e., location and value data for property insurance contracts an insurer has written) and estimates the damage of covered properties—the “severity” of a typhoon in contrast with the intensity (windspeed)—for each generated hazard. The most commonly used financial outputs are the Annual Average Loss (AAL) and the Exceedance Probability (EP) curve (a graph showing the probability that a certain level of losses will be exceeded).



**31. Our disaster scenarios are produced following a broadly similar modular approach.** The scenario is based on the recent WB DRFI program for the Government of the Philippines with technical support from Air Worldwide. The hazard module simulated thousands of possible ‘next years’ events to best reflect the scientific understanding of what is possible in the future. In the program, ten thousand simulated events were generated based upon detailed historical catalogs of typhoons to represent the range of potential future events. The simulated events are used to calculate the geographic distribution of hazard intensity associated with typhoons, such as wind speed. Then, these outputs of the hazard module were overlaid to the exposure data in the Philippines, which show the geographical distribution of private and public buildings and

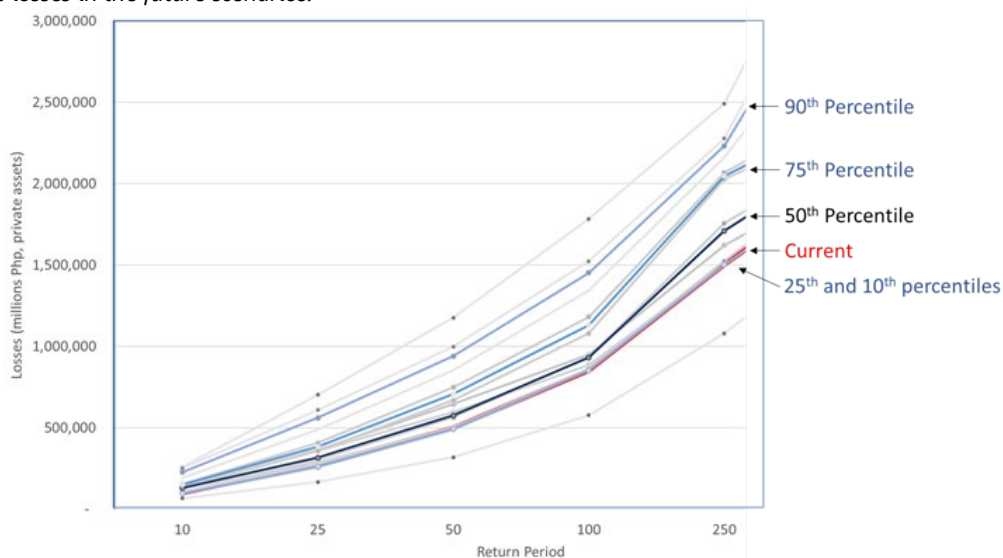
infrastructure and their values (irrespective of the availability of insurance). Then, the vulnerability module finally produced the damage rate for physical capital—the share of destroyed capital over the total stock of capital. Our last module is different from the insurers' cases. Instead of calculating financial impact directly (for example, by overlaying the damage rate per sub-region to bank loan data by location), we fed the damage rate information to the macrofinancial model as capital stock depreciation shock. This approach incorporates the general-equilibrium effects of the physical capital losses, not just the direct, partial equilibrium effects.

**32. For future damage scenarios, the catastrophe risk model must be recalibrated to represent a future climate condition.** We followed the approach outlined in Ranger and Niehörster (2012). We took the future number of typhoons, and their intensity from PAGASA's exercise for each of the five climate models explored in the study and used the hazard module in the CAR model to generate 10 thousand typhoons using these future parameters instead of current parameters. The next two modules (vulnerability and macrofinancial modules) are the same as the current scenario.

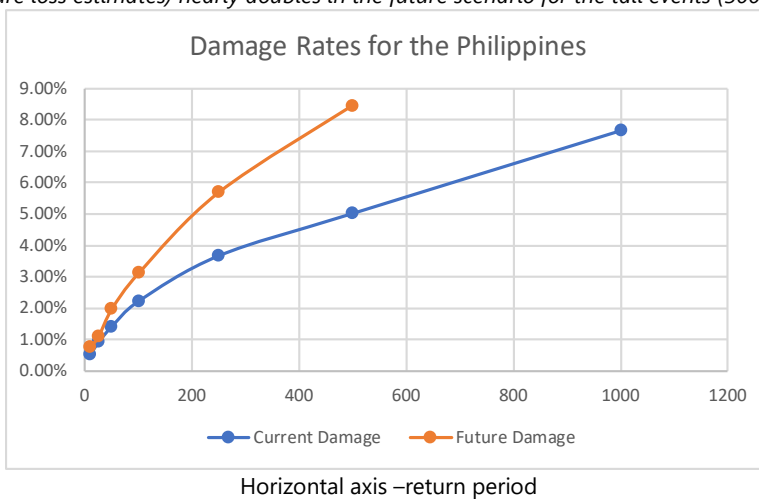
**33. Damage from typhoons is likely to increase in the future.** While PAGASA's exercise shows the total number of typhoons hitting the Philippines declines, there could be more intense typhoons. Given the non-linear relationship between wind-speed and damages, this leads to increases in typhoon risk for the majority of climate scenarios both in medium (once in 50 years) and tail (once in 250 years). Figure 6 shows the distribution of estimated damage for private sector assets in the Philippines from all the 50 thousand simulated typhoons (10 thousand each for five climate models). The model output shows wide ranges of potential losses, especially for tail events with longer return periods. For each return period, the future median losses are higher than current median losses, which corresponds to about 25 percentile losses in the future scenarios, indicating that damage is likely to increase in the future scenario. We used the higher estimated losses (90<sup>th</sup> percentile) for the stress test to make the exercise conservative (i.e., more severe).

**Figure 6. Estimated Physical Capital Losses<sup>1</sup>**

The model output shows wide ranges of potential losses, especially for tail events with longer return period. For each return period, the future median losses are higher than current median losses, which corresponds to about 25 percentile losses in the future scenarios.



As a result, the damage rate (the share of the value of lost physical capital over the value of existing stock in percent, using the 90<sup>th</sup> percentile future loss estimates) nearly doubles in the future scenario for the tail events (500 year return period).



Source: Authors

1/ The top chart covers private sector assets only, but the exercise has separate estimates for public assets as well.

## D. Macrofinancial Scenario

**34. Whether a disaster becomes a systemic macrofinancial shock or not depends on the size and diversification of an economy.** For small economies, one intense hurricane can have a devastating impact. For example, a Central American study found that a one standard deviation increase in a hurricane’s intensity leads to a decrease in total GDP per capita growth of 0.9–1.6 percent and a 3 percent decrease in total income (Ishizawa and Miranda 2016). Also, the literature suggests reconstruction after major disasters can last 5 to 10 years, magnifying the impacts of the shock on total GDP and consumption. However, for large and diverse economies, the

macro-level impact could be small, as was the hurricane Katrina in the U.S. in 2005. Indeed, the Federal Reserve Board continued to tighten monetary policy throughout 2005 and 2006, in response to inflationary pressures and strong overall macroeconomic growth. Most of the studies on the impact of Katrina have focused on the local economy and displaced population (see, for instance, Vigdor, 2008, Groen and Polivka, 2008, and Deryugina, Kawano, and Levitt, 2018). Moreover, they found that, even though the displacement was significant, about 400,000 people, the impact on their employment and income was small and transitory. The Philippines is much more geographically and economically diverse than island countries but much smaller than the U.S. Accordingly, it is not clear whether disasters could cause a systemic impact without a model-based analysis.

**35. To fully account for the economic impact of intense typhoons, including potentially long-lasting amplification effects, it is important to include the following channels in the model.**

- **Immediate physical destruction.** We interpret the shock as a one-time capital depreciation shock using the damage rates calculated in the previous section. To be precise, the damages estimated with the CAT risk model covers buildings and infrastructure and not all the capital used for production (such as manufacturing machines and computers). However, the damage rate is applied to all the capital stock as an approximation, assuming that other capital is geographically distributed in the same way as buildings and infrastructure.
- **Long-lasting decline in total factor productivity (TFP).** TFP declines as the reconstruction process does not immediately lead to output recovery (Hallegatte and Vogt-Schilb, 2019). For instance, affected sites need to be cleaned out for debris first before starting any reconstruction. The roads that remain usable may not be the “most important” roads that have the most traffic. The buildings that are still inhabitable are not the ones hosting the most important businesses. It is possible to reallocate a large share of capital over the medium term through investment and relocation (for instance, the most productive firms will move to inhabitable buildings). But it is almost impossible to reallocate most of the capital in the short run. The result is a drop in TFP, in addition to the decrease in capital stock. Empirical studies confirm that disasters reduce both the stock of capital and TFP (Bakkensen and Barrage 2018). They found that roughly one-third of the impact on GDP stems from capital destruction, and the other two-thirds are due to the accompanying TFP shock.
- **Time for reconstruction.** The modeling of the reconstruction duration is also critical: in a simple model with no financial and technical constraints, damages can be repaired in a few weeks or months. In reality, reconstruction takes much longer for financial, regulatory, and technical reasons:
  - 1) **Financial.** In many countries, the reconstruction of local infrastructure is paid for by the government but done by local authorities. However, budgetary processes can take months to transfer the resources from the central government to the local authorities, slowing down reconstruction. And private actors – firms and households – may be unable to mobilize



enough resources to rebuild at once and often decide to repair homes and factories in phases, spreading the cost over the years.

- 2) **Regulatory.** After a large shock, reconstruction requires long-term planning, in particular, if the goal is to “build back better.” For instance, it may be decided not to rebuild in the most at-risk areas. But doing so requires a political process that can take several months. And in the absence of pre-approved contracts and specific public financial management arrangements, procurement can also delay reconstruction by months or more.
- 3) **Technical.** Reconstruction increases demand in specific sectors that have capacity constraints. For instance, debris removal after a hurricane can take a long time because heavy equipment is missing. Or specific skills may be missing, like roofers or carpenters. The tension in some sectors can slow down reconstruction significantly and is visible in wages and prices in the construction sector (something referred to as “demand surge” in the literature and the insurance industry).

**36. At the same time this exercise did not explicitly consider the role of adaptation and mitigation.** Adaptation and mitigation could limit overall damages to the economy and banks. For instance, increasing the quality of infrastructure could reduce their damage on average. Developing property and catastrophe insurance markets, which are underdeveloped now, could limit the loss of property collateral values for bank loans and therefore loss-given-default (LGD). Pre-arranged contingent financing contracts with international financial organizations can boost public expenditures for responding to disasters. Since there is no comprehensive data that lists all the planned projects, and the impact of these measures on damages is uncertain, this exercise does not incorporate the potential effects of these measures.

**37. Even without tail events, there could be losses from moderate but more frequent disasters due to climate change.** The disaster risk scenario indicates that climate change would increase the annual average loss of physical capital because there would be more intense typhoons even though the expected number of total typhoons, including less powerful ones, will decline. The increase of damage rates based on annual average loss in the future scenario means a higher steady-state capital depreciation rate and, therefore, growth rate.

**38. The real business cycle (RBC) model described in Annex 2 was applied to incorporate the three channels:**

- **Immediate physical destruction.** To represent immediate losses of assets and capital, a shock  $z_{(d,t)}$  was applied to the depreciation rate of capital in the model  $\delta/z_{(d,t)}$ . A decline in  $z_{(d,t)}$  raises depreciation. The size of the shock was calibrated such that depreciation increases identical in magnitude to the modelled damages.
- **Long-lasting decline in total factor productivity.** TFP decreases in parallel to the increase in the depreciation rate. The GDP production function has the Cobb-Douglas form  $y_t = [k_{(t-1)}]^\alpha (z_{(y,t)} n_t)^{(1-\alpha)}$ . The shock  $z_{(y,t)}$  was calibrated to decline in magnitude twice as much as the

increase in depreciation. So, if depreciation increased from 2.5% to 6.5%, e.g., by four percentage points,  $z_{(y,t)}$  would fall from 1 to 0.92.

- **Time for reconstruction.** The model incorporates habits in consumption and investment adjustment cost, such that it takes time for households to adjust their consumption and time for firms to adjust their investment plans. In addition, the shock to the depreciation rate  $z_{(d,t)}$  is short-lived, while the TFP-shock  $z_{(y,t)}$  has long persistence (assuming that the allocation of capital and TFP gets back to its pre-disaster level eventually).

**Table 3. Philippines: Disasters' Impact on Capital and GDP**

(In percent)

Return period (years)/ episodes	Damage rate of capital: Current scenario	Damage rate of capital: Future scenario	Peak GDP decline: Current scenario <sup>2</sup>	Peak GDP decline: Future scenario
10	0.52	0.76	-0.73	-1.10
25	0.92	1.10	-1.31	-1.61
50	1.42	1.98	-2.04	-2.90
100	2.23	3.12	-3.28	-4.50
250	3.68	5.70	-5.36	-8.39
500	5.03	8.47	-7.39	-12.28
Annual average	0.23	0.31	...	-0.12 <sup>1</sup>
Memo items: Actual shocks to real GDP growth rate in the past crises				
Global financial crisis	...	...	-2.90	...
Asian financial crisis	...	...	-5.69	...
COVID-19 <sup>3</sup>	...	...	-14.49	...
1980s <sup>4</sup>	...	...	-16.50	...

Source: Author's estimation.

1/Steady state GDP growth rate difference from current scenario.

2/ For the past crisis, the difference of real GDP growth rate between the crisis-year and the year before. Only for the political turmoil episode on mid-1980s, the figure shows 1983 growth rate-1984 and 1985 growth rate since the country experienced two consecutive years of -7.3 percent contraction.

3/ Based on October 2020 WEO.

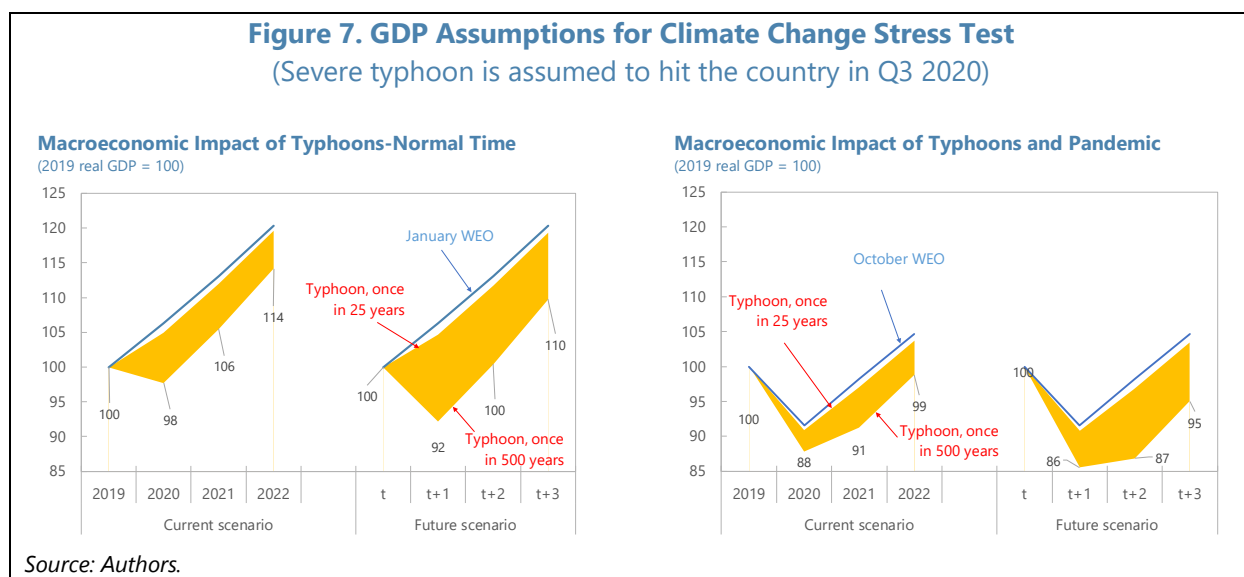
4/ The political turmoil-related crisis in 1984-85.

**39. The model simulation results indicate that extreme typhoons' impact on GDP growth could be systemic in the Philippines.** IMF staff estimate that the Philippines' potential growth rate is 6½ percent per year as of 2020. One standard deviation of the annual GDP growth rate (1980–2019) is 3½ percent. Table 3 shows that for both current and future scenarios, typhoons with 10- and 25-year return period give less than one standard deviation shock to GDP, which is also smaller than the shock

to the Philippines during the Global Financial Crisis or Asian Financial Crisis episodes. The difference between current and future scenarios is also small. The severity of the GDP impact and the difference between current and future scenarios becomes starker for tail events. In particular, the impact of a 500-year return period typhoon on real GDP is comparable to that of COVID-19.

**40. On the other hand, the incremental impact of climate change appears small.** The impact, measured by the reduction of annual average GDP growth rate in a steady state (-0.12 percentage points per year), appears small, especially given the strong potential growth rate of 6½ percent.

**41. Based on these results, we established ten macrofinancial scenarios for extreme typhoons taking baseline scenarios with and without COVID-19.** The baseline with COVID-19 is October 2020 WEO, and the baseline without pandemic is January 2020 WEO. There are four adverse scenarios for each baseline: once in 25- and 500-years typhoon using current and future disaster risks. We did not stress test for the incremental change scenario since the effect on GDP is minimal. As shown in Figure 7, the impact of a once in a 25-year typhoon is moderate across all four cases. The effects of climate change become more visible in tail typhoon events (once in 500 years).

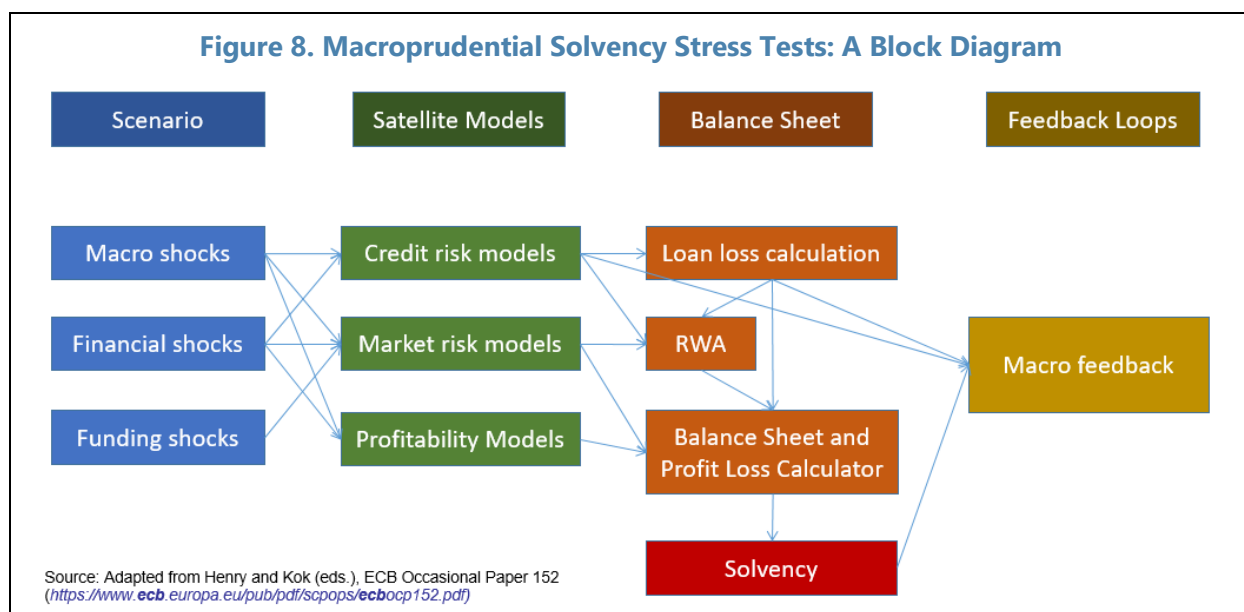


## E. Bank Solvency Stress Test

**42. The solvency stress test of banks follows the same standard FSAP method as applied for the macro scenario stress tests.** Annex 1 (STeM) and the TN on risk assessment provides the details. The solvency stress test assesses whether banks have adequate capital buffers to withstand a set of macrofinancial shocks envisioned under the four three-year horizon scenarios. While the macro scenario incorporates fiscal-monetary policy responses embedded in the baseline and the model, the tests do not account for regulatory relief/forgiveness and borrower-support measures undertaken upon COVID-19. Figure 8 illustrates selected elements of the solvency stress testing

framework. Scenarios influence the credit risk, market risk, and profitability of individual institutions. This, in turn, has an impact on banks' balance sheets and profit and losses via changes in the loan loss provisions, RWAs, and market gain/losses. Post stress capital is calculated by adjusting the initial capital ( $C_0$ ) of each institution with the stressed income ( $Income^*$ ) and the stressed RWA ( $RWA^*$ ), as follows:

$$CR^* = \frac{C_0 + Income^*}{RWA^*}$$

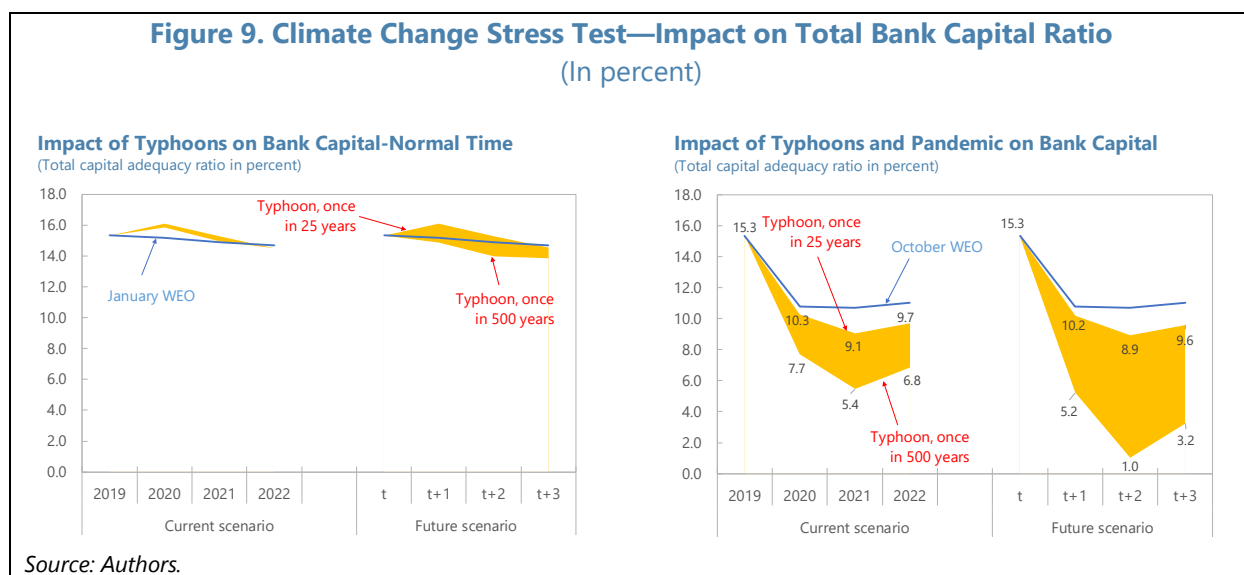


**43. Baseline macrofinancial forecast and bank balance sheet structure in the future scenario are assumed to be the same as the current scenario to identify the marginal effects of climate change.** Also, the tests assume a quasi-static balance sheet for the three years of stress test horizon. The allocation of assets and the composition of funding sources remain the same as the latest actual observation. Gross exposures in bank balance sheets, such as loans and holdings of debt securities, are assumed to grow in line with nominal GDP growth. Besides, banks are able to build capital buffers only through retained earnings.

**44. The results show that climate change may not cause extreme financial instability on its own (Figure 9).** Without other extreme tail events, such as a pandemic, climate change in the future would reduce bank capital ratio visibly only in the tail events once in 500 years. Still, the decline is small at one percentage point. Indeed, bank capital could rise immediately after the shock because of the positive effects of valuation gains from sovereign bond assets (about 25 percent of bank assets) from policy rate cuts that dominate over the negative effects of credit cost and other profitability shocks which emerge with longer lags. Also, the difference of capital ratios between baseline and a 500-year return period typhoon remains very small—maximum 0.2 percentage points in the current scenario and 0.9 percentage points in the future scenario.

**45. However, the possibility of compound risks drastically increases the marginal effects of a typhoon on top of a pandemic.** Even without climate change, the compound risk significantly increases the additional effects from typhoons for both 25- and 500-year disasters. Comparing the results of the current scenario under normal time and pandemic baselines, a joint materialization of typhoons and pandemic increases the marginal impact of typhoons by two percentage points for a 25-year return period typhoon and 5½ percentage points for a 500-year return period typhoon. In the future scenarios, a joint shock strengthens the additional impact of typhoons by 2.2 and nearly 8⅔ percentage points compared to the normal time baseline case.

**46. The joint shock also heightens the effects of climate change for extremely intense typhoons.** For 25-year return period events, the effects of climate change remain small (the difference of the impact of a 25-year return period event in the current and future scenarios). However, for 500-year return period events, the difference between current and future scenario with the pandemic rise to 4½ percentage points compared to one percentage point difference under normal time baseline.



**47. These relatively benign results should be interpreted with caution.** The exercise does not include all the climate change-related risks. It excludes damages from physical risk other than infrastructure damages from typhoons due to storm wind. Damages on agricultural harvest and properties due to storm precipitation and floods, which could worsen because of sea-level rise, are not included either. It also excludes the impact from transition risk, which could materialize in nearer future. Furthermore, the exercise focused only on macro-economic level transmission channels of severe typhoons. For example, it did not account for the impact on bank solvency from declined property collateral values that increases LGD due to data limitations. GDP losses could be larger if typhoon destroys key infrastructure such as roads, ports, airports, and utility generation and distribution systems that have spillover effects to broader economic activities instead of, for example, residential areas. The overall impact on bank capital could become noticeable if all types of climate change risks and industry or company-level transmission channels are accounted for.

## POLICY DISCUSSION

### A. Policy Decision Making Under “Deep” Uncertainty

**48. The level of uncertainty in climate science and financial stability stress tests for climate change is much “deeper” than the uncertainty economists are used to.** Traditional approach for decision making under uncertainty in science, finance, and economics is expected value analysis. Agents understand a system’s structure and nature of uncertainty sufficiently well so that they can put probability over potential outcomes and then formulate optimal policies to maximize expected utility (so-called predict-then-act framework, see Lempert and others, 2013). Modern macroeconomic models with general equilibrium structures and rational expectations are based on such premises to formulate optimal monetary or fiscal policies. However, the type of uncertainty climate scientists face is so “deep” that agents cannot even put probabilities over potential outcomes (see, for example, Lempert and others, 2003, and Millner and others, 2013, and Ranger and Niehorster, 2012). For instance, it is hard to put probability distribution over various RCPs and specific GHG and temperature pathways for each RCP, which are subject to enormous model and scenario (which also depends on human behavioral adjustment) uncertainties. Such a case with unquantifiable uncertainty is an example of deep uncertainty (also called ambiguity).

**49. Historically, an alternative to the predict-then-act framework to cope with tail risks and greater uncertainty has been scenarios, namely, stress tests.** Scenario analysis sheds light on tail events that have very low probability but extremely high impact. These events may not affect optimal policy choice under the predict-then-act framework since their likelihood is very low. Finance and financial stability communities faced serious limitations of the probabilistic risk management approach that focuses on expected values when extreme but plausible tail risk materialized. The CAT risk models, which rely on simulated hazard scenarios, became popular in the industry after a tail risk (Hurricane Andrew in the U.S.) revealed the weakness of the probabilistic (i.e., actuarial) approach and pushed many insurers into insolvency. Bank and financial system stress testing has become a standard tool to assess vulnerabilities to financial stability risks after the Global Financial Crisis. In the context of broader IMF policy work, the guidance note on the IMF’s post-program monitoring ([IMF, 2017](#)) emphasized the importance of risk scenario analysis to assess borrowing members’ capacity to pay.

**50. More recently, climate policy discussions started to emphasize the importance of good decision making under deep uncertainty.** In climate policy discussions, national authorities need to decide on adaptation and mitigation policies that would have long-term effects for decades to come (i.e., infrastructure, utility provision, urban planning etc.,) under deep uncertainty over future climate pathways. The probabilistic approach could encourage gridlock when participants argue over projections rather than solutions. The approach could also lead to overconfidence and choose solutions that fail when the future turns out differently (Lempert and others, 2013, Ranger and Niehorster, 2012, and their references). One alternative method that combines the strength of the probabilistic and scenario-based approaches is Robust Decision Making (RDM). RDM regard quantitative models as mapping assumptions to consequences instead of the best representation of

reality. It attempts to increase the value of decision-makers' existing models (made for predict-then-act analysis) by running them numerous times (possibly with different calibrations and behavioral assumptions) to identify vulnerabilities of considered policy options and find plans that are robust over many combinations of assumptions.<sup>19</sup> There are several other methods to address the issue of deep uncertainty systematically.

**51. The deep uncertainty with climate change means that we should be cautious when drawing policy conclusions from stress test results.** Our stress tests are subject to deep uncertainty at multiple levels, climate scenario, climate model for the Philippines, CAT risk model, macrofinancial model, and stress testing model. Therefore, trying to draw prudential policy implications at this stage is premature. Before moving into prudential policy discussion, it seems important to first explore the sensitivity of the climate change stress tests vis-à-vis alternative models and parameter assumptions at each step of the test.

## B. Recommendation

**52. At this stage, more exploratory work to examine the potential impact of climate change on financial stability are the areas where the Philippines' authorities should be focusing.** As for physical risks, inter-agency collaboration, including non-economic agencies such as PAGASA, DOE, and DA, is critical. Given the country's vulnerabilities to disaster risks, there appears to be substantial work going on to set a broad strategy to cope with climate change and disaster risk management. It will be important for the BSP as well as the Insurance Commission to tap into these resources on climate science. As for transition risks, they seem to be coming from the power generation sector and the need to rebalance their long-term energy plans to shift from coal-based power plants to renewable sources, which could be accompanied by electricity price increases. The issue of deep model and scenario uncertainty should be taken into these works explicitly, and a variety of models and scenarios could be considered. The FSAP exercise could be considered as one of the first steps to do so.

**53. To increase the confidence in stress test results, it is also essential to improve data.** As for the banking sector data, it will be good to increase the granularity of the exposure data by industries and locations. Collecting LTV data would be helpful to assess risks from real estate loans (irrespective of whether the BSP uses it as a prudential tool or not). Also, further strengthening the

---

<sup>19</sup> An example discussed in Lempert and others (2013) is the long-term urban water management plan in California by the Southern California's Inland empire Utilities Agency (IEUA). In their plan established in 2005, they aimed to meet growing regional demand by increasing groundwater use and recycled water. But the plan did not incorporate the effects of climate change. So, the RAND corporation helped the agency to revisit the original plan using the RMD framework. They run 200 simulations, each one based on a given set of assumptions about the future climate, the agency's ability to implement its plan, and future socioeconomic condition, then visualized the cost of plan and the present value of cost of any water shortages. The exercise identified 120 cases where the 2005 plan failed to meet the agency's goals. The analysis of the simulation results showed that, out of the six uncertain parameters considered, only a specific combination of three lead to failures (i.e., the vulnerability of the 2005 plan); a 10 percent or greater increase in precipitation, a 3-percent or greater drop in the average precipitation that percolates into the regions aquifers, and larger-than-expected climate effects on imports. These are key parameters that the agency needs to monitor regularly and possibly consider adjusting the plan if the identified vulnerability is likely to materialize.

disclosure requirements could enrich information on firms' and financial institutions' exposures to climate change risks. Such information would be helpful to identify more micro-level channels of the linkages between climate change and financial stability.



CLIMATE CHANGE STRESS TEST OF BANK SOLVENCY		
1. Institutional Perimeter	Institutions included	<ul style="list-style-type: none"> <li>• 46 UKBs</li> </ul>
	Market share	<ul style="list-style-type: none"> <li>• 92 percent of the banking system by assets.</li> </ul>
	Data and baseline date	<ul style="list-style-type: none"> <li>• Supervisory data (balance sheet and income statements).</li> <li>• Started position: December 2019</li> <li>• Data on a 'solo basis.'</li> </ul>
2. Channels of Risk Propagation	Methodology	<ul style="list-style-type: none"> <li>• Solvency stress test—the same as macro scenario stress tests, including risk factors, satellite models, and various micro and behavioral assumptions (such as LGD) following IMF solvency stress test workbook.</li> <li>• Climate scenario—constructed by combining climate science, catastrophe risk, and macrofinancial models.</li> </ul>
	Risk factors	<ul style="list-style-type: none"> <li>• Physical risks—extreme weather events (typhoons) affecting bank solvency through their macrofinancial impact.</li> <li>• Credit Risk: Satellite models per bank type to estimate loan losses. Regression model for logit transformed PDs. Regressors include the lagged dependent variable and contemporaneous and lagged macroeconomic variables: GDP growth, short term rates, term spread, unemployment, stock price, and exchange rate.</li> <li>• Market risk: valuation losses for HFT and AFS securities are calculated using a Mark to Market (MTM) approach. Valuation losses for held-to-maturity (HtM) securities are calculated using a credit risk approach. As a sensitivity analysis, an MTM approach is used for HtM securities.</li> <li>• Net interest income: A gap analysis is conducted based on granular data on asset/liability structure of individual banks broken into types of funding sources and time to re-pricing buckets. Interest margin shocks vary per scenario.</li> <li>• Pre-impairment income for banks: Income in the absence of shocks is assumed to stay at the level observed for 2019 with the additional feature that non-performing loans will not generate any income</li> </ul>
	Test horizon	<ul style="list-style-type: none"> <li>• Three years upon a severe disaster.</li> <li>• <i>Current scenario</i>: A typhoon shock materializes in 2020, using end-2019 balance sheet data and distribution of typhoons (frequency and severity) as of 2020.</li> <li>• <i>Future scenario</i>: A typhoon shock materializes sometime in mid-21<sup>st</sup> century, using end-2019 balance sheet data and distribution of typhoons as of mid-21<sup>st</sup> century.</li> </ul>
3. Climate scenario	Scenario formulation method	<ul style="list-style-type: none"> <li>• Scenarios consist of climate science, disaster, and macrofinancial scenarios. <ul style="list-style-type: none"> <li>○ <i>Climate scenario</i> provides the future distribution of typhoon intensity (windspeed) and frequencies for the Philippines using climate science model, based on a given global climate scenario. FSAP scenarios are based on the 2018 exercise by the Philippine Atmospheric, Geophysical, and</li> </ul> </li> </ul>

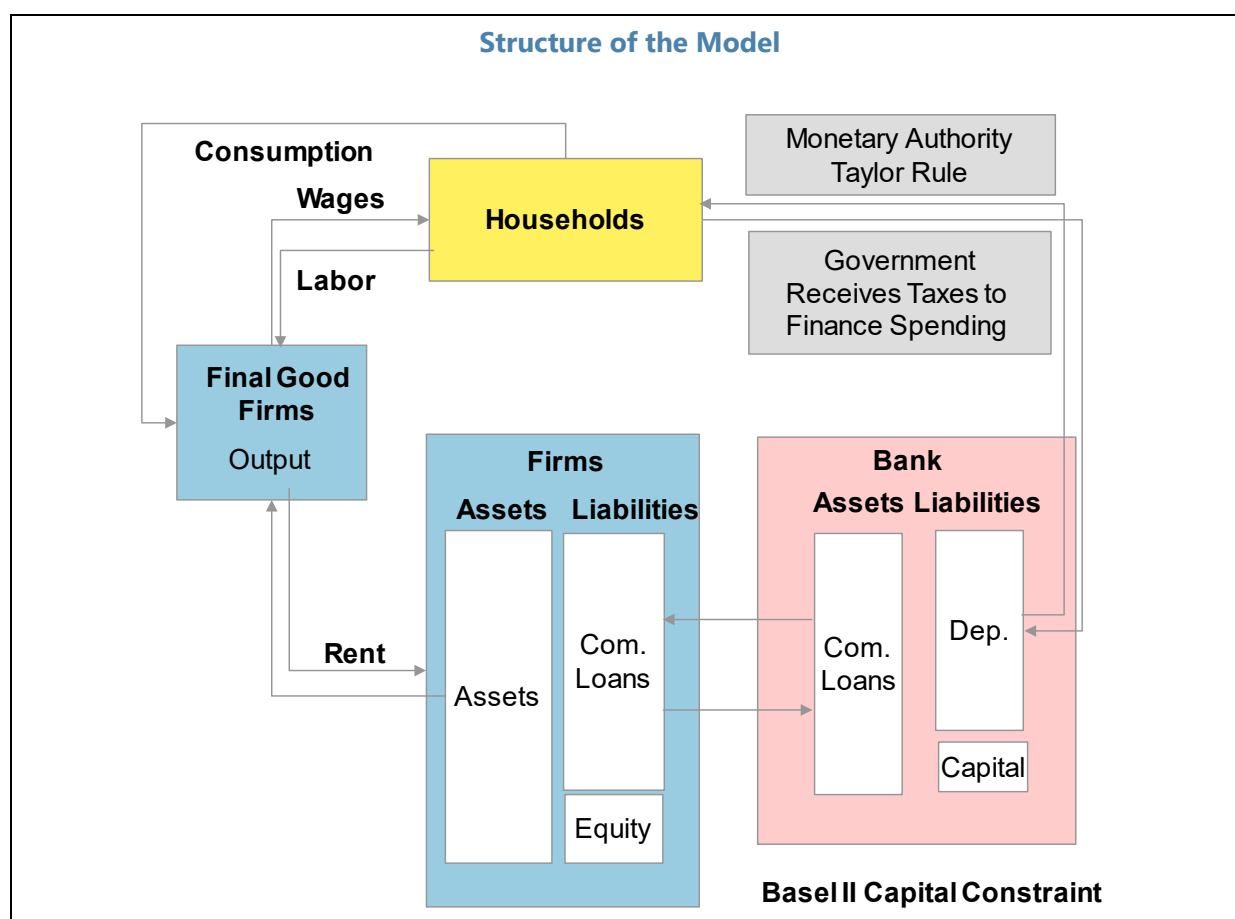
		<p>Astronomical Services Administration. It shows the impact of an internationally-accepted global scenario from IPCC (RCP 8.5—a high greenhouse gas emission scenario with little global-scale mitigation policies and technological advancement) for the mid-21st century. The global temperature would increase by 1.4-2.6°C above the 1986-2005 levels. For the Philippines, such climate change is likely to increase the average intensity (windspeed) of typhoons but reduce the average number of typhoons hitting the country.</p> <ul style="list-style-type: none"> <li>○ <i>Disaster scenario</i> provides the estimate of typhoon's damages (physical capital losses in percent of existing stock) for a given likelihood (25-500 return period, namely, once in 25-500-year probability). For a given climate scenario, ten thousand possible losses from disasters are simulated using the catastrophe-risk model developed under the World Bank disaster risk financing and insurance program with the Government of the Philippines. While it considers direct destruction from typhoons, the additional effects from sea-level rise nor flood are not included. For each return period, the mission uses the losses at the 90<sup>th</sup> percentile of the ten thousand simulation results for the future scenario (the losses under the current scenario roughly correspond to the 25<sup>th</sup> percentile of the simulation results.)</li> <li>○ <i>Macrofinancial scenario</i> is constructed by a staff-developed Dynamic Stochastic General Equilibrium (DSGE) model calibrated for the Philippines. The physical damage is modeled as a capital depreciation shock, which also causes correlated productivity shocks in line with empirical findings in disaster/infrastructure economics (1/3 of the impact comes from short-lived capital depreciation and 2/3 from persistent productivity shocks). The model also includes adjustment costs with investment, slowing capital accumulation and, therefore, recovery.</li> </ul>
4. Tail shocks	Size of the shock	<ul style="list-style-type: none"> <li>• Two baseline economic scenarios before applying typhoon shocks. <ul style="list-style-type: none"> <li>○ <i>Normal time</i>: January 2020 WEO forecast (before COVID-19 shock), in line with the potential growth rate of 6½ percent.</li> <li>○ <i>Pandemic</i>: October 2020 WEO forecast that includes the impact of COVID-19. These scenarios consider the realization of two extreme events—pandemic and severe typhoons.</li> </ul> </li> <li>• The severity of typhoons is measured by the value of destroyed physical capital in percent of existing capital (for both current and future scenarios), for 25-500 return periods (i.e., once in 25-500-years event). In the insurance industry, insurers price disaster insurance aiming at the losses under 100-year return period. They examine the adequacy of their reserves for tail events (250-500 years return period).</li> </ul>
5. Risks and buffers	Risks/factors assessed (How each element is derived, assumptions.)	<ul style="list-style-type: none"> <li>• Credit risk (provision costs)</li> <li>• Market risk, including FX risk</li> <li>• Stress on pre-provision profits, including interest margin</li> </ul>

	Behavioral adjustments	<ul style="list-style-type: none"> <li>• Balance sheet growth assumption: Quasi-Static—balance sheet size/GDP remains constant.</li> <li>• Balance sheet composition remaining constant over the stress test horizon.</li> <li>• Banks can only accumulate capital through the retained earnings.</li> <li>• Banks pay dividends only if net income after taxes is positive, with the dividend payout ratio consistent with individual banks' 2019 ratios for UKBs.</li> <li>• Tax rate: 30% (corporate tax rate for banks)</li> </ul>
6. Regulatory and market-based standards and parameters	Calibration of risk parameters	<ul style="list-style-type: none"> <li>• PDs: proxies based on actual and estimated new NPL flows over performing loans. PDs for banks with limited credit information is taken as the weighted average PD of the rest of the institutions.</li> <li>• LGDs: 68 percent for UKBs based on average historical provision coverage ratio (provisions/NPLs) that appear consistent with cross-bank type variation over collection and cure rate of NPLs.</li> <li>• Cure rates with respect to NPL(t-1): 10 percent for UKBs based on historical averages. In addition, an extra cure rate of 18 percent on New NPLs (t-1) is assumed for UKBs in 2021. This, given the concentration of their loan portfolio to the Manila metropolitan area (99% of total loans), which has been the focus of the lockdown measures. Thus, it is assumed that some of the loan defaults of 2020 are driven by shortage in liquidity rather than solvency issues.</li> </ul>
	Regulatory and accounting and market-based standards	<ul style="list-style-type: none"> <li>• Basel II standardized approach.</li> <li>• RWAs evolve with credit growth, net of increases in provisions. RWAs are further adjusted by the new NPLs that are not provisioned (to reach the weight of 150% required by regulation).</li> </ul>
7. Reporting Format for Results	Output presentation	<ul style="list-style-type: none"> <li>• The level of real GDP and aggregate CAR chart for five years for current and future scenarios showing the range of potential outcomes of the baselines (without disaster shocks) and stress scenarios (with typhoon shock ranging from once in 25-500-year severity.)</li> </ul>

## Appendix II. Macrofinancial Model

### A. Overview

1. The model is a simplified version of Lipinsky and Miescu (2020) and adapted for the economic and financial structure of the Philippines. It has household, firms, banks, monetary authority, and the government with the following interactions.



### B. Households

2. Households maximize expected lifetime utility  $E_0 \sum_{t=0}^{\infty} \beta^t U_t$ , subject to a budget constraint. Households obtain utility from consumption  $c_t$ , subject to internal habit formation  $h > 0$ , and disutility from sending  $n_t$  members to work. Their preferences take the following form:

$$U_t = \frac{z_{c,t}(c_t - hc_{t-1})^{1-\sigma}}{1-\sigma} - \frac{\tau_n n_t^{1+\phi}}{1+\phi}$$

We call  $z_{c,t}$  a demand shock, because it increases the demand for consumption and induces households to work more. Regarding the budget constraint, households consume  $c_t$ , and put

savings  $d_t$  in a bank account. On the income side, they receive wage income  $w_t n_t$  in return for providing labor, interest income  $\frac{R_{d,t-1}}{\pi_t} d_{t-1}$  on savings,  $\Pi_{i,t} = q_t i_t - i_t(1 + S)$  from capital goods producers that provide capital goods  $i_t$  to firms at price  $q_t$ , and face quadratic cost of producing capital, and profits  $\Pi_{y,t}$  from final good firms.

$$c_t + d_t = w_t n_t + \frac{R_{d,t-1}}{\pi_t} d_{t-1} + \Pi_{i,t} + \Pi_{y,t}$$

### 3. The optimization problem is expressed as follows.

$$\begin{aligned} \max \mathcal{L} = E_0 \sum_{t=0}^{\infty} \beta^t & \left[ \frac{z_{c,t} (c_t - h c_{t-1})^{1-\sigma}}{1-\sigma} - \frac{\tau_n n_t^{1+\phi}}{1+\phi} \right] \\ & - \lambda_t \left[ c_t + d_t - \left( w_t n_t + \frac{R_{d,t-1}}{\pi_t} d_{t-1} + q_t i_t - i_t \left( 1 + S \left( z_{i,t} \frac{i_t}{i_{t-1}} \right) \right) \right) + \Pi_{y,t} \right] \end{aligned}$$

The first order conditions with respect to consumption  $c_t$ , labor  $n_t$ , saving  $d_t$ , and investment  $i_t$  are:

$$\begin{aligned} \partial c_t: z_{c,t} & \left( (c_t - h c_{t-1})^{-\sigma} - h \beta E_t \left[ \frac{z_{c,t+1}}{z_{c,t}} (c_{t+1} - h c_t)^{-\sigma} \right] \right) - \lambda_t = 0 \\ \partial n_t: & -\tau_n n_t^\phi + \lambda_t w_t = 0 \\ \partial d_t: & -1 + \beta E_t \left[ \frac{\lambda_{t+1}}{\lambda_t} \frac{R_{d,t}}{\pi_{t+1}} \right] = 0 \\ \partial i_t: & q_t - \left( 1 + S \left( z_{i,t} \frac{i_t}{i_{t-1}} \right) \right) + S' \left( z_{i,t} \frac{i_t}{i_{t-1}} \right) z_{i,t} \frac{i_t}{i_{t-1}} + \beta E_t \left[ \frac{\lambda_{t+1}}{\lambda_t} S' \left( z_{i,t+1} \frac{i_{t+1}}{i_t} \right) z_{i,t+1} \left( \frac{i_{t+1}}{i_t} \right)^2 \right] = 0 \\ & S \left( z_{i,t} \frac{i_t}{i_{t-1}} \right) = \frac{\phi_i}{2} \left( z_{i,t} \frac{i_t}{i_{t-1}} - 1 \right)^2 \end{aligned}$$

### Firms

**4. Firms invest  $q_t k_t$  in productive assets  $k_t$ . Firms finance assets with commercial loans  $l_t$  from the bank, and with equity  $n_{F,t} = q_t k_t - l_t$ .** Next period, they receive a gross return on assets equal to  $R_{k,t+1} = r_{k,t+1} + (1 - \delta) q_{t+1}$ , consisting of a rental rate of capital  $r_{k,t+1}$  and the value of assets after depreciation  $(1 - \delta) q_{t+1}$ , and pay a share  $\Gamma_{t+1}$  of the earnings to the bank in return for the loans. Firms' cashflow is:

$$-n_{F,t} + E_t \left( M_{t+1} \left( R_{k,t+1} k_t (1 - \Gamma_{t+1}) \right) (1 - \tau) \right)$$

## C. Banks

**5. The bank intermediates funds between households and firms.** It receives funds  $d_t$  from households, promising a return  $R_{d,t}$  and provides  $l_t$  commercial loans to firms. The remainder is financed with equity  $n_{B,t} = l_t - d_t$ . Next period the bank receives the share  $\Gamma_{t+1}$  of earnings  $R_{k,t+1}k_t$  from firms. A part of the firms default, incurring default costs  $R_{k,t+1}k_t\mu\Delta_{t+1}$  for the bank. The bank's cashflow and objective is:

$$-n_{B,t} + E_t \left( M_{t+1} \left( R_{k,t+1}k_t(\Gamma_{t+1} - \mu\Delta_{t+1}) - \frac{R_{d,t}}{\pi_{t+1}}d_t \right) (1 - \tau) \right)$$

**6. While the firm sector cannot go under ( $R_{k,t+1}k_t(1 - \Gamma_{t+1}) > 0$ ), the value of assets of the bank may fall below the value of liabilities.** To shield the bank from default, it adopts a Basel II capital constraint:

$$\frac{R_{k,t+1}k_t(\overline{\Gamma_{t+1}} - \overline{\mu\Delta_{t+1}})}{\pi_{t+1}} d_t \geq 0$$

Even if the gross return  $R_{k,t+1}$  falls to  $R_{k,t+1} \equiv \theta_t E_t(R_{k,t+1})$ , the bank remains solvent. We call  $\theta_t$  value-at-risk shock, because it quantifies the downside risk for the bank.

**7. The optimization problem of the bank is to maximize its cashflow subject to the Basel capital constraint and the participation constraint of firms,**

$$\begin{aligned} \max_{\{l_t, n_{B,t}, R_{k,t}\}} \mathcal{L} = & -n_{B,t} + E_t \left( M_{t+1} \left( \frac{R_{k,t+1}}{q_t} (n_{F,t} + l_t) (\Gamma(\varepsilon_{t+1}^*) - \mu\Delta(\varepsilon_{t+1}^*)) - \frac{R_{d,t}}{\pi_{t+1}}d_t \right) (1 - \tau) \right) \\ & + \lambda_t^V E_t \left( M_{t+1} \left( \frac{R_{k,t+1}}{q_t} (n_{F,t} + l_t) (\overline{\Gamma(\varepsilon_{t+1})} - \overline{\mu\Delta(\varepsilon_{t+1})}) - \frac{R_{d,t}}{\pi_{t+1}}d_t \right) \right) \\ & + \lambda_{F,t} \left( -n_{F,t} + E_t \left( M_{t+1} \left( \frac{R_{k,t+1}}{q_t} (n_{F,t} + l_t) (1 - \Gamma(\varepsilon_{t+1}^*)) \right) (1 - \tau) \right) \right) \end{aligned}$$

where  $d_t = l_t - n_{B,t}$ .

**8. To build intuition, it should be noted that income of firms and the bank are taxed at rate  $\tau > 0$ ,** while households don't pay taxes on deposits. Accordingly, financial intermediation yields a return equal to  $\tau \frac{R_{d,t}}{\pi_{t+1}} d_t$ , or making us of the Basel II capital constraint:

$$\tau \left( \frac{R_{k,t+1}k_t(\overline{\Gamma_{t+1}} - \overline{\mu\Delta_{t+1}})}{\pi_{t+1}} \right)$$

**9. Commercial loans are chosen optimally trading off the benefit of financial intermediation  $\tau \left( \frac{R_{k,t+1}k_t(\overline{\Gamma_{t+1}} - \overline{\mu\Delta_{t+1}})}{\pi_{t+1}} \right)$  versus the cost of default  $-R_{k,t+1}k_t\mu\Delta_{t+1}(1 - \tau)$ .**

We can show that  $\Gamma_{t+1}$  and  $\Delta_{t+1}$  depend on  $\varepsilon_{t+1}^*$

$$\varepsilon_{t+1}^* = \frac{R_{l,t} l_t}{\pi_{t+1} R_{k,t+1} k_t}$$

$$\Gamma(\varepsilon_{t+1}^*) \equiv \Delta(\varepsilon_{t+1}^*) + \varepsilon_{t+1}^*(1 - F(\varepsilon_{t+1}^*)), \Gamma'(\varepsilon_{t+1}^*) = 1 - F(\varepsilon_{t+1}^*)$$

$$\Delta(\varepsilon_{t+1}^*) \equiv \int_0^{\varepsilon_{t+1}^*} \varepsilon_{t+1} f(\varepsilon_{t+1}) d(\varepsilon_{t+1}), \Delta'(\varepsilon_{t+1}^*) = f(\varepsilon_{t+1}^*) \varepsilon_{t+1}^*$$

and  $\overline{\Gamma}_{t+1}$  and  $\overline{\Delta}_{t+1}$  on  $\overline{\varepsilon}_{t+1}$

$$\overline{\varepsilon}_{t+1} = \frac{R_{l,t} l_t}{\theta_t \pi_{t+1} R_{k,t+1} k_t}$$

such that choice of the lending rate implies the marginal trade-off of higher cost of default versus the higher benefit of financial intermediation.

$$\frac{\partial \left( -R_{t+1} k_t \mu \Delta_{t+1} (1 - \tau) + \tau \left( \frac{R_{k,t+1}}{k_t} \left( \overline{\Gamma}_{t+1} - \mu \overline{\Delta}_{t+1} \right) \right) \right)}{\partial R_{l,t}}$$

$$= (-\mu f(\varepsilon_{t+1}^*) \varepsilon_{t+1}^* (1 - \tau) + \tau (1 - F(\overline{\varepsilon}_{t+1}) - \mu f(\overline{\varepsilon}_{t+1}) \overline{\varepsilon}_{t+1})) l_t / \pi_{t+1}$$

**10. Furthermore, it should be noted that  $\Gamma_{t+1}$  and  $\Delta_{t+1}$  as well as  $\overline{\Gamma}_{t+1}$  and  $\overline{\Delta}_{t+1}$  depend on  $\sigma_{F,t}$ , as emphasized by Christiano, Motto and Rostagno (2014), called idiosyncratic or default risk shock. A higher value of  $\sigma_{F,t}$  results in more mass in the tail of the distribution, a higher value of  $F(\varepsilon_{t+1}^*)$ , and more firm defaults.**

**11. Solution to banks' optimization has the following characteristics.**

- **The bank provides commercial loans ( $\partial l_t$ )** such that the return equals the cost:

$$\partial l_t: E_t \left( M_{t+1} \left( \frac{R_{k,t+1}}{q_t} X_{t+1} - \frac{R_{d,t}}{\pi_{t+1}} (1 - \tau + \lambda_t^V) \right) \right) = 0$$

The standard first order condition in model with capital accumulation is  $1 = E_t \left( M_{t+1} \left( \frac{R_{k,t+1}}{q_t} \right) \right)$  or

$E_t \left( M_{t+1} \left( \frac{R_{k,t+1}}{q_t} - \frac{R_{d,t}}{\pi_{t+1}} \right) \right) = 0$ . In contrast, the factor  $X_{t+1}$  enters here, including the cost of default

$-\mu \Delta(\varepsilon_{t+1}^*)$  and the benefit of financial intermediation  $\lambda_t^V \theta_t \left( \Gamma(\overline{\varepsilon}_{t+1}) - \mu \Delta(\overline{\varepsilon}_{t+1}) \right)$ :

$$X_{t+1} \equiv \left( \lambda_{F,t} (1 - \Gamma(\varepsilon_{t+1}^*)) + \left( \Gamma(\varepsilon_{t+1}^*) - \mu \Delta(\varepsilon_{t+1}^*) \right) \right) (1 - \tau) \\ + \lambda_t^V \theta_t \left( \Gamma(\overline{\varepsilon}_{t+1}) - \mu \Delta(\overline{\varepsilon}_{t+1}) \right)$$

- **The bank chooses equity ( $\partial n_{B,t}$ )**, internalizing that more equity loosens the Basel II capital constraint.

$$\partial n_{B,t}: -1 + E_t \left( M_{t+1} \frac{R_{d,t}}{\pi_{t+1}} (1 - \tau + \lambda_t^V) \right) = 0$$

- **The bank chooses commercial loan rates ( $\partial R_{l,t}$ )** such that  $X_{t+1}$  is maximized and invariant to changes in the default threshold that is  $\frac{\partial X_{t+1}}{\partial \varepsilon_{t+1}^*, \varepsilon_{t+1}} = 0$ . The bank chooses the commercial loan lending rate equating the marginal cost of more defaults to the marginal benefit of financial intermediation.

$$\partial R_{l,t}: E_t \left( \frac{M_{t+1}}{\pi_{t+1}} \left( \left( \lambda_{F,t} \left( -(1 - F(\varepsilon_{t+1}^*)) \right) + (1 - F(\varepsilon_{t+1}^*) - \mu f(\varepsilon_{t+1}^*) \varepsilon_{t+1}^*) \right) (1 - \tau) \right. \right. \\ \left. \left. + \lambda_t^V (1 - F(\overline{\varepsilon}_{t+1}) - \mu f(\overline{\varepsilon}_{t+1}) \overline{\varepsilon}_{t+1}) \right) \right) = 0$$

### Stock Price Gaps

12. **Firms accumulate net worth  $n_{F,t}$  out of retained earnings, distributing a share  $\gamma_D$  of earnings and receiving a fixed equity injection equal to  $\omega$ .**

$$n_{F,t} = R_{k,t} k_{t-1} (1 - \Gamma(\varepsilon_t^*)) (1 - \tau) (1 - \gamma_D) + \omega$$

However, firms' target net worth  $n_{F,t}^*$  results from choosing net worth optimally:

$$\partial n_{F,t}: \lambda_{F,t} = 1$$

Comparing the solutions between realized and target net worth, provides deviations from the optimum. For the stock price, the gap is called stock price gap:

$$spg = \frac{q_t - q_t^*}{q_t^*}$$



## D. Equilibria

**13. In the optimal solution ( $\partial n_{F,t}$ :  $\lambda_{F,t} = 1$ ), the participation constraint of firms determines  $n_{F,t}$ , the optimality condition with respect to  $l_t$  determines  $k_t$  and hence  $l_t = q_t k_t - n_{F,t}$ , and the Basel II capital constraint determines  $d_t$  and hence  $n_{B,t} = l_t - d_t$ . The optimality condition with respect to  $n_{B,t}$  together with the optimality condition of households with respect to  $d_t$  imply  $\lambda_t^V > 0$ .**

**14. In the realized (suboptimal) model solution,  $n_{F,t}$  is given through the exogenous law of motion.** Then, the participation constraint of firms determines  $k_t$  and hence  $l_t = q_t k_t - n_{F,t}$ . The optimality condition with respect to  $l_t$  determines  $\lambda_{F,t}$ , which is time varying. While  $d_t$  and  $\lambda_t^V$  are determined as above.

## E. The Financial System and Market Clearing

**15. An agent representative for the financial sector smooths dividends  $c_{FS,t}$  by maximizing lifetime utility  $E_0 \sum_{t=0}^{\infty} \beta^t U_t^{FS}$**

$$U_t^{FS} = \frac{z_{c,t} (c_{FS,t} - hc_{FS,t-1})^{1-\sigma}}{1-\sigma}$$

and aggregates income across firms and the bank. The budget constraint of the financial sector is,

$$c_{FS,t} + q_t k_t - d_t = \left( R_{k,t} k_{t-1} (1 - \mu \Delta_t) - \frac{R_{d,t-1}}{\pi_t} d_{t-1} \right) (1 - \tau)$$

and the stochastic discount factor is

$$M_{t+1} = \beta \frac{\lambda_{FS,t+1}}{\lambda_{FS,t}}$$

where  $\lambda_{FS,t}$  is the LaGrange multiplier associated to the budget constraint.

## F. Final Good Firms, Inflation and Monetary Policy

**16. Final good firms rent capital  $k_{i,t-1}$  from firms, hire workers  $n_{i,t}$  from households, and choose prices  $p_{i,t}$ , subject to quadratic adjustment cost,**

$$\frac{\varphi}{2} \left( \frac{p_{i,t}}{p_{i,t-1}} - 1 \right)^2 y_t = \frac{\varphi}{2} \left( \pi_t \frac{p_{i,t}}{p_{i,t-1}} - 1 \right)^2 y_t, \quad \pi_t \equiv \frac{p_t}{p_{t-1}}, \quad p_{i,t} \equiv \frac{p_{i,t}}{p_t}, \quad \eta_t = \eta_{ss} z_{\eta,t},$$

$$\max \left\{ \Pi_{y,i,t} = p_{i,t} y_{i,t} - r_t k_{i,t-1} - w_t n_{i,t} - \frac{\varphi}{2} \left( \pi_t \frac{p_{i,t}}{p_{i,t-1}} - 1 \right)^2 y_t \right\}$$

$$y_{i,t} = k_{i,t-1}^\alpha (z_{y,t} n_{i,t})^{1-\alpha}$$

$$y_{i,t} = p_{i,t}^{-\eta_t} y_t$$

resulting in the following optimization problem:

$$\max \left\{ p_{i,t} y_{i,t} - r_t k_{i,t-1} - w_t n_{i,t} - \frac{\varphi}{2} \left( \pi_t \frac{p_{i,t}}{p_{i,t-1}} - 1 \right)^2 y_t + p_{m,i,t} \left( k_{i,t-1}^\alpha (z_{y,t} n_{i,t})^{1-\alpha} - y_{i,t} \right) + v_{i,t} (p_{i,t}^{-\eta_t} y_t - y_{i,t}) \right\}$$

**17. A symmetric equilibrium implies the following first order conditions, after making use of  $\partial y_{i,t}: v_t = 1 - p_{m,t}$ ,**

$$\partial k_{i,t-1}: r_t = p_{m,t} \alpha \frac{y_t}{k_{t-1}}$$

$$\partial n_{i,t}: w_t = p_{m,t} (1 - \alpha) \frac{y_t}{n_t}$$

$$\partial p_{i,t}: p_{m,t} = 1 - \frac{1}{\eta_t} \left( 1 - \varphi \pi_t (\pi_t - 1) + \varphi \beta E_t \left( \frac{\lambda_{t+1}}{\lambda_t} \pi_{t+1} (\pi_{t+1} - 1) \frac{y_t}{y_{t-1}} \right) \right)$$

**18. The monetary authority sets interest rates according to a Taylor rule:**

$$\frac{R_{d,t}}{R_{d,ss}} = \left( \frac{R_{d,t-1}}{R_{d,ss}} \right)^{\gamma_R} \left( \frac{\pi_t}{\pi_{ss}} \right)^{(1-\gamma_R)\gamma_\pi} \left( \frac{y_t}{y_{ss}} \right)^{(1-\gamma_R)\gamma_y} e^{\sigma_m \epsilon_{m,t}}$$

**19. In a simple real-business-cycle model without inflation, the problem would simplify.**

Final good firms would rent capital  $k_{t-1}$  from firms and hire workers  $n_t$  from households.

$$\max \{ y_t - r_t k_{t-1} - w_t n_t \}$$

$$y_t = k_{t-1}^\alpha (z_{y,t} n_t)^{1-\alpha}$$

**20. The first order conditions with respect to capital and labor would yield equations for the return on capital  $r_t$  and wages  $w_t$ :**

$$\partial k_{t-1}: r_t = \alpha \frac{y_t}{k_{t-1}}$$

$$\partial n_t: w_t = (1 - \alpha) \frac{y_t}{n_t}$$

## G. Shocks and Shock Processes

21. The model has three macro shocks, a consumption preference shock  $z_{c,t}$ , an investment adjustment cost shock  $z_{i,t}$ , and a TFP shock  $z_{y,t}$ ,

$$\ln(z_{c,t}) = \rho_c \ln(z_{c,t-1}) + \sigma_c \epsilon_{c,t}$$

$$\ln(z_{i,t}) = \rho_i \ln(z_{i,t-1}) + \sigma_i \epsilon_{i,t}$$

$$\ln(z_{y,t}) = \rho_y \ln(z_{y,t-1}) + \sigma_y \epsilon_{y,t}$$

two shocks related to monetary policy, a price elasticity shock  $z_{\eta,t}$  ( $\eta_t = \eta_{ss} z_{\eta,t}$ ), and a monetary policy shock  $\sigma_m \epsilon_{m,t}$  in the Taylor rule,

$$\ln(z_{\eta,t}) = \rho_\eta \ln(z_{\eta,t-1}) + \sigma_\eta \epsilon_{\eta,t}$$

and two financial shocks, an aggregate corporate risk shock  $z_{\theta,t}$  ( $\theta_t = \theta_{ss} z_{\theta,t}$ ), and an idiosyncratic corporate risk shock  $\sigma_{F,t}$ ,

$$\ln(z_{\theta,t}) = \rho_\theta \ln(z_{\theta,t-1}) + \sigma_\theta \epsilon_{\theta,t}$$

$$\ln(\sigma_{F,t}) = (1 - \rho_{\sigma_F}) \sigma_{F,ss} + \rho_{\sigma_F} \ln(\sigma_{F,t-1}) + \sigma_{\sigma_F} \epsilon_{\sigma_F,t}$$

## H. Data

22. We use three macroeconomic time series—real GDP growth, investment growth and employment growth, two series related to monetary policy—the GDP deflator as a proxy for the price level and the policy rate, and two financial time series—stock price growth, and corporate credit spreads.

Shocks	Data
TFP Shock	Real GDP Growth
Investment Adjustment Cost Shocks	Investment Growth
Demand Shock	Employment Growth
Monetary Policy Shock	GDP Deflator/ Inflation
Elasticity of Substitution between Goods Shock	Policy Rate
Aggregate/ Value-at-Risk Shock	Stock Price Growth
Idiosyncratic/ Default Risk Shock	Lending Spread

## I. Parameters

**23. The following parameters (before adding shocks) were calibrated.** The remaining parameters were estimated using Philippine data.

Parameter	Description	Value
$\alpha$	power on capital in production function	0.30
$\beta$	discount rate	0.99
$\delta$	depreciation rate of capital	0.025
$h$	habit parameter	0.75
$\sigma$	power on consumption	1.00
$\phi$	curvature on disutility of labor	1.00
$\tau_n$	disutility weight on labor	4.00
$\tau$	corporate tax rate	0.20
$\mu$	loss-given-default	0.40
$\gamma_D$	payout rate	0.03
$\omega$	household equity injection; such that in steady state	$\lambda_{F,t} = 1$
$\theta_{ss}$	steady state value-at-risk	0.95

## REFERENCES

- AIR Worldwide, 2017. [Climate Change Impacts on Extreme Weather](#), White Paper.
- Bank of England (BoE), 2019. [The 2021 biennial exploratory scenario on the financial risks from climate change](#).
- Batten, S., Sowerbutts, R., & Tanaka, M., 2016, Let's Talk About the Weather: The Impact of Climate Change on Central Banks. [Bank of England Working Paper, No. 603](#).
- Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., and Visentin, G., 2017, A climate stress-test of the financial system. *Nature Climate Change*, 7(4), 283–288.
- Campiglio, E., Dafermos, Y., Monnin, P., Ryan-Collins, J., Schotten, G., and Tanaka, M., 2018, Climate change challenges for central banks and financial regulators. *Nature Climate Change*, 8(6), 1–13.
- De Nederlandsche Bank (DNB), 2017. [Waterproof?](#) An exploration of climate-related risks for the Dutch financial sector.
- \_\_\_\_\_, 2019. [An energy transition risk stress test for the financial system of the Netherlands](#), Occasional Studies Volume 16-7.
- Deryugina, T., Kawano, L. and Levitt, S., 2018. The economic impact of Hurricane Katrina on its victims: evidence from individual tax returns. *American Economic Journal: Applied Economics*, 10(2), pp.202-33.
- Feyen, E. H., Utz, R. J., Zuccardi Huertas, I. E., Bogdan, O., and Moon, J., 2020, Macro-Financial Aspects of Climate Change. World Bank Policy Research Working Paper, (9109).
- Gallo, F., J. Daron, I. Macadam, T. Cinco, M. Villafuerte II, E. Buonomo, S. Tucker, D. Hein-Griggs, and R. Jones, 2018, High-resolution regional climate model projections of future tropical cyclone activity in the Philippines, [International Journal of Climatology, Vol. 39, Issue 3](#).
- Good, P., Lowe, J., Ridley, J., Bamber, J., Payne, T., Keen, A., Stroeve, J., Jackson, L., Srokosz, M., Kay, G., Harper, A., Kruijt, B., Burke, E., Abbott, B., O'Connor, F., Minshull, T., Turley, C. and Williamson, P., 2014, An updated view of tipping points and the relevance for long-term climate goals.
- Groen, J.A. and Polivka, A.E., 2008. The effect of Hurricane Katrina on the labor market outcomes of evacuees. *American Economic Review*, 98(2), pp.43-48.
- Hallegatte, S. and A. Vogt-Schilb, 2016. Are losses from natural disasters more than just asset losses? The role of capital aggregation, sector interactions, and investment behaviors, Policy Research Working Paper, No. 7885. World Bank.

International Monetary Fund (IMF), 2017. World Economic Outlook, October 2017. Chapter 3: The Effects of Weather Shocks on Economic Activity: How Can Low-Income Countries Cope?

Intergovernmental Panel on Climate Change (IPCC), 2013. Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

\_\_\_\_\_, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge United Kingdom and New York, NY, USA, pp. 688.

Leaton, J., Ranger, N. Ward, R., Sussams, L. and Brown, M., 2013, Unburnable Carbon 2013 – Wasted Capital and Stranded Assets. Carbon Tracker Initiative and London School of Economics and Political Science.

Lempert, R.J., S. Popper, and S. Bankes, 2003, Shaping the next one hundred years: new methods for quantitative, long-term policy analysis. [Rand Corporation](#).

Lempert, R.J., Popper, S.W., Groves, D.G., Kalra, N., Fischbach, J.R., Bankes, S.C., Bryant, B.P., Collins, M.T., Keller, K., Hackbarth, A. and Dixon, L., 2013. Making good decisions without predictions: Robust decision making for planning under deep uncertainty. [RAND Corporation Research Brief](#).

Lipinsky, F. and Miescu, M.S., 2020. *Capital Gaps, Risk Dynamics, and the Macroeconomy* (IMF Working PaperNo. 2020/209). International Monetary Fund.

Lloyd's, 2014. [Catastrophe modelling and climate change](#).

McKinsey, 2020. [Climate risk and response](#).

Millner, A., Dietz, S. and Heal, G., 2013. Scientific ambiguity and climate policy. *Environmental and Resource Economics*, 55(1), pp.21-46.

Nelson, G., H. Valin, R., Sands, P. Havlick, H. Ahammad, D. Derynge, J. Elliott, S. Fujimori, T. Hasegawa, E. Heyhoe, P. Kyle, M. Von Lampe, H. Lotze-Campen, D. d'Croz, H. van Meijl, D., van der Mensbrugghe, C. Müller, A. Popp, R. Robertson, S. Robinson, E. Schmid, C. Schmitz, A. Tabeau, and D. Willenbockel, 2014, Climate change effects on agriculture: economic responses to biophysical shocks, Proceedings of the National Academy of Sciences of the U.S.A. (PNAS), Vol. 11, No. 9.

Network of Central Banks and Supervisors Greening Financial System (NGFS), 2019. Technical supplement to the First NGFS Comprehensive Report

\_\_\_\_\_, 2020a. Guide for Supervisors: Integrating climate-related and environmental risks into prudential supervision

\_\_\_\_\_, 2020b. Guide to climate scenario analysis for central banks and supervisors.

\_\_\_\_\_, 2020c. The macroeconomic and financial stability impacts of climate change: Research Priorities

Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA), 2018: Observed and Projected Climate Change in the Philippines. Philippine Atmospheric, Geophysical and Astronomical Services Administration, Quezon City, Philippines.

Ranger and Niehörster, 2012, Deep uncertainty in long-term hurricane risk: Scenario generation and implications for future climate experiments. *Global Environmental Change* Volume 22, Issue 3, August 2012, Pages 703-712

Reinders, H.J., Schoenmaker D., van Dijk, M., 2020, A finance approach to climate stress testing. CEPR discussion paper.

Rogelj, J., Popp, A., Calvin, K. V, Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., & Marangoni, G., 2018, Scenarios towards limiting global mean temperature increase below 1.5 C. *Nature Climate Change*, 8(4), 325.

Smale, R., Hartley, M., Hepburn, C., Ward, J., and Grubb, M., 2006, The impact of CO2emissions trading on firm profits and market prices. *Climate Policy*, 6(1), 31–48.

UNEP-Acclimatise, 2018. [Navigating a New Climate: Assessing credit risk and opportunity in a changing climate. Part 2](#): Physical risks and opportunities.

UNEP-Oliver Wyman, 2018. [Extending Out Horizons: Assessing credit risk and opportunity in a changing climate. Part 1](#): Transition-related risks and opportunities.

Vermeulen, R., Schets, E., Lohuis, M., Kölbl, B., and Jansen, D., 2019, The Heat is on: A framework measuring financial stress under disruptive energy transition scenarios. DNB Working Paper, 625.

Vigdor, J., 2008. The economic aftermath of Hurricane Katrina. *Journal of Economic Perspectives*, 22(4), pp.135-54.